COMPLEX Final Scientific Report, Volume 2
Non-linearities and System-Flips

Edited by Nick Winder and Hans Liljenström

With contributions from the COMPLEX Consortium
http://owsgip.itc.utwente.nl/projects/complex/

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C O M P L E X
Knowledge Based Climate Mitigation Systems for a Low Carbon Economy

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11. Actor-based System Dynamics Modelling of Abrupt Climate Change Scenarios

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This report describes the applications of the Structural Dynamic Economic Model (SDEM) to modelling of abrupt climate change as a catastrophic climate scenario. The potential slowdown/shutdown of Atlantic thermohaline circulation (Atlantic THC) is studied as an example.

SDEM is a stylized prototype of MADIAMS (the Multi-Actor Dynamic Integrated Assessment Model System) and, therefore, is a member of **the MADIAMS model family.**[13] A substantial part of the MADIAMS model family has been developed within EU FP7 COMPLEX project. The main members of MADIAMS model family are global-scale actor-based system dynamics Integrated Assessment models (IAMs) designed within a classical IAM conceptual scheme presented on Fig. 11.1.

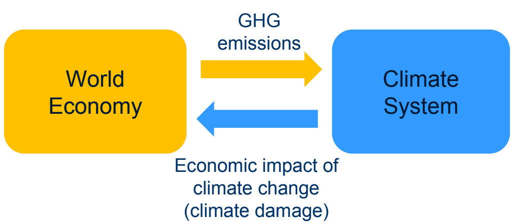

Figure 11.1. *A conceptual scheme of Integrated Assessment modelling (IAM), also applicable to members of MADIAMS model family*

[13] A dedicated MADIAMS model family homepage is maintained at the Global Climate Forum website, URL: http://www.globalclimateforum.org/madiams

These models consist of two major modules: the economic module describing the global economy, and the climate module describing the global climate. Economy affects climate through anthropogenic greenhouse gas (GHG) emissions (represented in SDEM/MADIAMS by CO_2 emissions). There is also a feedback from climate system to economic system parameterized through introduction of climate damage function(s).

Therefore, these members of MADIAMS model family follow the classical IAM scheme where the coupled climate-socioeconomic scenarios at the global level (including the dynamics of carbon emissions) are computed self-consistently, and in this respect there is no need to incorporate in the modelling framework any external ('exogenous') quantitative emissions/ climate scenarios like RCPs or SRES.

In the context of the present paper, SDEM may be seen as the 'minimal' climate-economic model able to generate regimes of abrupt/irreversible climate change.

The economic module of SDEM is developed within an innovative *actor-based system dynamics approach* which, in brief, might be seen as further development of 'traditional' system dynamics (SD) economic modelling, however with a much stronger focus on describing behaviour and decision making of key aggregate actors of economic system, often – if not to say always – under conditions of conflict of actors' interest.

The version of SDEM described here is a model of the aggregate world economy. The population of the model world is divided into two social classes: entrepreneurs and wage-earners, described by two aggregated actors. Full employment is assumed. Wage-earners consume everything they earn, i.e. their consumption is equal to wages. Entrepreneurs 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, these forms of capital are assumed to be non-substitutable, and the production function corresponds in the general case to the Leontief form. Model runs have been made for 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), from which they first have to pay 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 reduction 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. It is assumed that the decision-making of entrepreneurs can be described by a simple control strategy formalized as a dynamic rule. It should be stressed that no utility maximization/ intertemporal optimization procedures are assumed in the actor-based system dynamics modelling framework.

The dynamic equations of the normal economy (including equations for physical capital, for human capital and for wages) 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.

Carbon emissions are computed in SDEM/MADIAMS by converting the output of modelled sectors of the economy (specified by relevant production functions, usually of Leontief type) into emissions through scaling factors like energy efficiency and carbon efficiency specific to the sector under consideration. The energy and carbon efficiency, in their turn, are state variables for which the dynamic equations are specified describing their endogenous improvement due to target investment (i.e. due to recirculation of collected carbon tax revenues into the economy in the form of green R&D investment).

The economic modules of the models developed within the MADIAMS model family can be linked to different climate modules. For instance, in the initial version of MADIAM[14] the carbon cycle – climate model NICCS[15] was incorporated.

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14 Weber, M., Barth, V., Hasselmann, K. (2005): A Multi-Actor Dynamic Integrated Assessment Model (MADIAM) of induced technological change and sustainable economic growth. *Ecological Economics,* **54,** 306-327.

15 Hooss, G., Voss, R., Hasselmann, K., Maier-Reimer, E., Joos, F. (2001): A Nonlinear Impulse response model of the coupled Carbon cycle – Climate System (NICCS). *Climate Dynamics,* **18,** 189-202.

In the present version of SDEM, in case of modelling the gradual climate change, a simple climate module consisting of dynamic equations for CO_2 concentration and for global mean surface air temperature is adopted.[16] For abrupt climate change simulations, a four-box model of the Atlantic THC (schematically presented on Fig. 11.2) is linked to this simple climate module.[17]

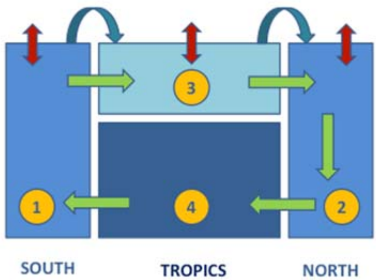

Figure 11.2. *Schematic of the four-box model of the Atlantic thermohaline circulation (THC) developed by Zickfeld et al. (2004)*

It is broadly acknowledged in IAM literature that projections generated by IAMs are very sensitive to the specification of the climate damage function(-s), and SDEM is no exception in this respect. Simulations with SDEM for a business-as-usual (BaU) scenario (no climate mitigation policies) and for

16 Kellie-Smith, O., Cox, P.M. (2011): Emergent dynamics of the climate-economy system in the Anthropocene. *Philosophical Transactions of the Royal Society* A, **369,** 868-886.

17 Zickfeld, K., Slawig, T., Rahmstorf, S. (2004): A low-order model for the response of the Atlantic thermohaline circulation to climate change. *Ocean Dynamics,* **54,** 8-26.

five alternative climate mitigation scenarios (implying global harmonized carbon tax rates of 10, 20, 30, 40, and 50 USD/tCO_2 respectively[18]), have been performed assuming two alternative specifications of the climate damage function: a (weakly nonlinear) quadratic function:

$$1 - d_N(T) = \frac{1}{1 + 0.0028(\Delta T)^2} \tag{11.1}$$

dependent on the temperature increase above the pre-industrial level, proposed by Nordhaus for his seminal DICE model,[19] and widely used later by other authors; and a (strongly nonlinear) function

$$1 - d_W(T) = \frac{1}{1 + (\Delta T / 20.46)^2 + (\Delta T / 6.081)^{6.754}} \tag{11.2}$$

proposed by Weitzman.[20] As shown on Fig. 11.3, 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.

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[18] All monetary variables are expressed in constant 2000 USD.

[19] Nordhaus, W.D. (2008): *A Question of Balance.* Yale University Press, New Haven & London.

[20] Weitzman, M.L. (2012): GHG targets as insurance against catastrophic climate damages. *Journal of Public Economic Theory,* **14,** 221-244.

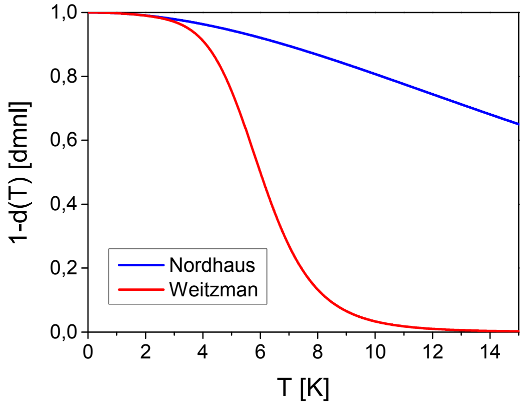

Figure 11.3. *The (weakly nonlinear) Nordhaus climate damage function (blue line) and the (strongly nonlinear) Weitzman climate damage function (red line).*

The results for the 21st and 22nd centuries computed with the SDEM model for **gradual climate change** conditions (no Atlantic THC module) are presented on Fig. 11.4 (global mean temperature) and Fig. 11.5 (effective GWP, i.e. Gross World Product, reduced through climate damage) for the Weitzman climate damage function (Eq. (11.2)). Fig. 11.4 indicates that a global carbon tax is a highly efficient instrument for reducing GHG emissions: the long-term temperature increases are significantly lower for higher carbon tax rates. Moreover, Fig. 11.5 indicates that mitigation scenarios are also economically sustainable in the long term. While the BaU scenario maintains the most rapid economic growth throughout the 21st century, it ultimately leads to a global economic collapse in the 22nd 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 22nd century. However, even the scenario with the most stringent mitigation policy presented in the figures leads to a 'four-degree world' – a dangerous but unfortunately quite plausible option of global climate-socioeconomic dynamics broadly discussed in recent publications.

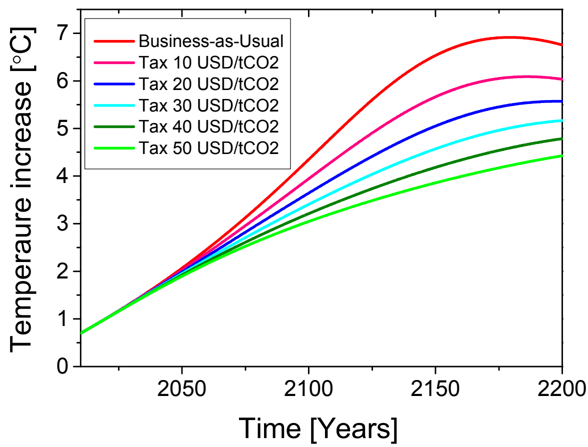

Figure 11.4. *Global mean surface air temperature increase above pre-industrial level projected by SDEM for a business-as-usual scenario (BaU) and five alternative mitigation scenarios with different global carbon tax rates.*

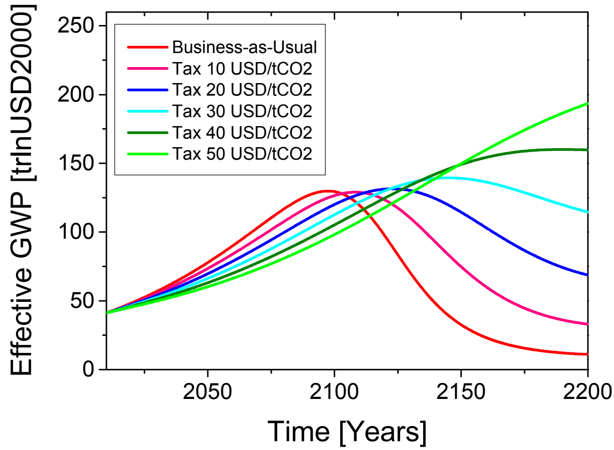

Figure 11.5. *Effective GWP (corrected for climate damage) projected by SDEM for the business-as-usual scenario (BaU) and five alternative mitigation scenarios with different global carbon tax rates*

Fig. 11.6 shows the SDEM simulations under **abrupt climate change** conditions. The model runs are made until the end of the 23rd century (the Atlantic THC module is activated). The overturning, measured in Sverdrups (Sv), is shown for the same six scenarios as before (BaU and five alternative carbon tax rates).[21] As seen from Fig. 11.6, the BaU scenario and the scenario with the lowest carbon tax rate considered lead to a shutdown of the THC in the long term (one of the tipping points in the climate system is therefore reached), while in scenarios with a stronger mitigation action the initial

[21] Note that no additional climate damages arising from possible abrupt climate change have been introduced into the climate damage function.

reduction of the THC is later reversed, the THC recovering in the long term.

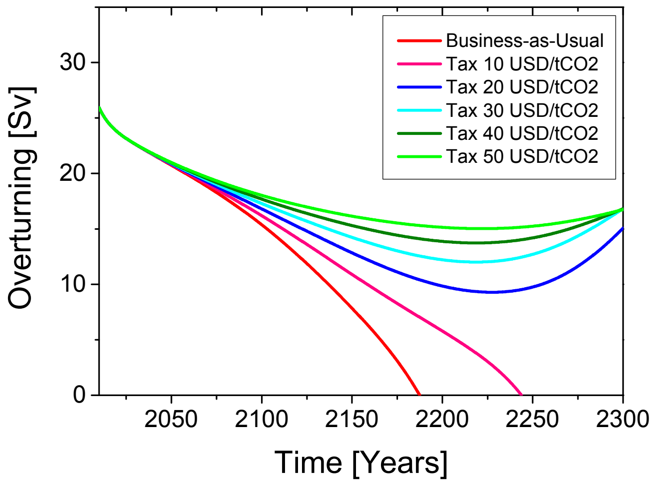

Figure 11.6. *Strength of Atlantic thermohaline overturning circulation, projected by SDEM for the business-as-usual scenario (BaU) and five alternative mitigation scenarios with different global carbon tax rates*