COMPLEX

Knowledge Based Climate Mitigation Systems for a Low Carbon Economy

Report on Integration of Climate Scenarios in the Modeling System

Date	**17.11.2015**
Report Number	**D5.4**
VERSION NUMBER:	2
Main Authors:	Kovalevsky, Dmitry V. (NIERSC) Arto, Iñaki (BC3) Dhavala, Kishore (BC3) Filatova, Tatiana (UT) Hasselmann, Klaus (MPG) Moghayer, Saeed M. (TNO) Niamir, Leila (UT) Voinov, Alexey (UT)

DIFFUSION LEVEL – PU

PU	**PUBLIC**
RIP	**RESTRICTED INTERNAL AND PARTNERS**
RI	**RESTRICTED INTERNAL**
CO	**CONFIDENTIAL**

Coordinator: Dmitry V. Kovalevsky, NIERSC

INFORMATION ON THE DOCUMENT

Title	Report on integration of climate scenarios in the modeling system
Authors	Kovalevsky, D.V., I. Arto, K. Dhavala, T. Filatova, K. Hasselmann, S.M. Moghayer, L. Niamir, and A. Voinov
Cite this report as:	Kovalevsky, D.V., I. Arto, K. Dhavala, T. Filatova, K. Hasselmann, S.M. Moghayer, L. Niamir, and A. Voinov (2015). Report on integration of climate scenaria in the modeling system. EU FP7 COMPLEX. Report D5.4, November 2015: 24 p.

DEVELOPMENT OF THE DOCUMENT

Date	Version	Prepared by	Institution	Approved by	Note
11.11.2015	V1	D.V. Kovalevsky	NIERSC		
17.11.2015	V2	L. Niamir	UT		Updating the references

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1. Introduction

The need for use of climate scenarios for modeling the coupled climate-energy-economic (CEE) systems arises from substantial multi-level uncertainties related to systems under study. Instead of attempts for 'predicting' the future, working with scenarios helps to evaluate the key uncertainties making the future unpredictable, particularly those ones that are determined by human influence on climate change. The scenarios provide plausible descriptions of possible futures at qualitative and quantitative levels, including such dimensions as socioeconomic and environmental conditions, technological change, emissions of greenhouse gases (GHGs) and aerosols, and climate change (Moss et al., 2010).

Moss et al. (2010) provide a useful classification of scenarios important for climate research, including:

- **Emissions scenarios:** quantifications of potential discharges to the atmosphere of substances affecting the radiation balance of the Earth (notably GHGs and aerosols);
- **Climate scenarios:** representations of potential future climate conditions (including the dynamics of such key climate variables as e.g. temperature and precipitation) at global and regional levels;
- **Environmental scenarios:** representations of possible changes of environmental conditions other than climate and potentially occurring regardless of climate change (e.g. water availability and quality at basin scale);
- **Vulnerability scenarios:** representations of various (mostly human-related) factors affecting vulnerability, including changes in demography, economic development, policy measures, and also cultural and institutional characteristics of different societies.

EU FP7 COMPLEX modeling system makes use of emissions/climate scenarios. The main purpose of this report is to describe the approaches for incorporating climate scenarios in different models of EU FP7 COMPLEX modeling system (Sec. 3 below). As will be seen from Sec. 3, these approaches are versatile, end even definitions of climate scenarios themselves vary from one model to another. Therefore, in the present report the term "climate scenario" is understood in a broad sense, covering all four specific scenario definitions adopted from (Moss et al., 2010) and presented above.

The rest of the report is organized as follows. Sec. 2 provides an overview of established approaches to incorporating climate scenarios in models of economics of climate change and includes historical notes on earlier scenario work (Sec. 2.1), an overview of SRES scenarios (Sec. 2.2) and a description of parallel approach to scenario development adopted for preparation of IPCC AR5 (IPCC, 2014) including the development of RCPs, SSPs, and SPAs (Sec. 2.3). Sec. 3 provides a detailed description of approaches for incorporating climate scenarios in different models of EU FP7 COMPLEX modeling system: GCAM (Sec. 3.1), MADIAMS/SDEM (Sec. 3.2), EXIOMOD (Sec. 3.3), and ABM (Sec. 3.4). Sec. 4 provides an extended example and further elaborates on the overview of endogenous climate scenario generation in MADIAMS/SDEM outlined in Sec. 3.2. Particularly, Sec. 4.1 includes a brief description of one of the latest versions of SDEM model developed within EU FP7 COMPLEX; Sec. 4.2 presents gradual climate change scenarios generated with SDEM; and

Sec. 4.3 presents abrupt climate change scenarios obtained with SDEM when the Atlantic thermohaline circulation (Atlantic THC) module is plugged in. Sec. 5 concludes.

2. Approaches to incorporating climate scenarios in models of economics of climate change

2.1. Earlier work on climate scenarios

It should be noted that, historically, the first area in which the scenario approach as such was broadly applied was military planning. Starting from 1960s, the scenario approach penetrates into strategic planning of various public and private organizations of different scales (Moss et al., 2010).

In climate research, an important domain of scenario phase space was initially occupied by spatial and temporal analogue scenarios, but later the model-based scenarios started playing an increasingly important role. The first generation of model-based scenarios were merely the quantified assumptions about potential future increases of CO_2 atmospheric concentrations (typically, doubling or quadrupling of CO_2) used as forcing in climate models of several first generations. Quantitative research of this kind that can be traced back as far as to the pioneering study of Arrhenius (1896) (see also historical notes in (Hasselmann, 2013)) still plays important role in modern climate science (e.g. (Geoffroy et al., 2013)).

Over time, climate scenarios were becoming more and more detailed (an instructive graphical presentation of a brief history of climate scenario development is provided on Figure 1 in (Moss et al., 2010), see also references to relevant publications therein).

Soon after its establishment in 1988, the Intergovernmental Panel on Climate Change (IPCC) has started developing, updating and using comprehensive climate scenarios on a regular basis. In 1990 IPCC issued Scenario A (SA90) that included a ‘business-as-usual’ (BaU) future emissions trajectory as well as three alternative policy scenarios. The next milestone was publication by IPCC of the IS92 scenarios (1992) on which IPCC TAR (IPCC, 2001) and partially IPCC AR4 (IPCC, 2007) were based. In 1996 IPCC decided to develop a new generation of scenarios that later became known as SRES scenarios (see Sec. 2.2 below).

2.2. IPCC AR4: SRES emissions scenarios

The Special Report on Emissions Scenarios (SRES) was published by IPCC in 2000 (SRES, 2000). The SRES scenarios were used in IPCC TAR (IPCC, 2001) and IPCC AR4 (IPCC, 2007) investigating the uncertainty of GHG and short-lived pollutants emissions under a wide possible range of driving forces. The time horizon of SRES scenarios is by year 2100.

The emissions projections for the following substances affecting the radiative balance of Earth were included in SRES: anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), hydrochlorofluorocarbons (HCFCs), chlorofluorocarbons (CFCs), the aerosol precursor and the chemically active gases sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs).

Geographically, emissions were provided aggregated into four world regions, and also as global totals. No feedback effect of future climate change on emissions from biosphere and energy has been assumed.

Unlike previous scenarios, the SRES projections consisted not only of the quantitative part, but were also supplemented by 'storylines' (narratives of possible futures). Totally four alternative narrative storylines were developed, and all quantitative emissions scenarios based on the same storyline are referred to as a 'scenario family':

- **A1** – scenarios of a more integrated world (with subsets **A1FI** – an emphasis on fossil fuels, **A1B** – a balanced emphasis on all energy sources, **A1T** – emphasis on non-fossil energy sources);
- **A2** – scenarios of a more divided world;
- **B1** – scenarios of a world more integrated, and more ecologically friendly;
- **B2** – scenarios of a world more divided, but more ecologically friendly.

In such a way, a pretty large set of selected scenarios (totally 40 scenarios) was divided into six scenario groups (A1FI, A1B, A1T, A2, B1, B2) that "should be considered equally sound" (SRES, 2000). It should be mentioned that though some of the scenarios were designed and labeled as more 'ecologically friendly' than others, in fact all SRES scenarios are 'baseline' (or 'reference') scenarios not including any climate mitigation policies (like e.g. the Kyoto Protocol to UNFCCC). All the scenarios are also considered 'neutral' in a sense they do not project future disasters or catastrophes (wars, conflicts, environmental collapse etc.). Overall, the set of SRES scenarios was developed to comprehensively represent the range of driving forces and emissions in scenario literature available at that time, excluding, however, 'surprise' or 'disaster' outliers.

2.3. IPCC AR5: RCPs, SSPs, and SPAs

2.3.1. Representative Concentration Pathways (RCPs)

While the sequential approach was adopted to developing the SRES and earlier scenarios, in the process of preparation of IPCC AR5 (IPCC, 2014) it was replaced by the parallel approach (Moss et al., 2010).

One of the key activities within this parallel scenario development process was the elaboration of four **Representative Concentration Pathways (RCPs) –** a scenario set containing emission, concentration and land-use trajectories (van Vuuren et al., 2011).

The RCPs are labelled according to radiative forcing target level (relative to pre-industrial level) in 2100. Therefore, **RCP2.6, RCP4.5, RCP6, and RCP8.5** correspond to radiative forcing in 2100 equal to 2.6, 4.5, 6, and 8.5 W/m^2, respectively. Each of the RCPs covers the period 1850-2100, however, by request of climate modeling community, the RCPs are supplemented with (stylized) extensions (Extended Concentration Pathways, ECPs) spanning to 2300.[1]

For each RCP, the following information is available:

[1] It should be noted that two alternative ECPs correspond to RCP6, known as ECP6 and ECP-SCP.

- **Emissions** of CO_2, CH_4, N_2O, HFCs, PFCs, CFCs, SF_6, SO_2, Black Carbon (BC), Organic Carbon (OC), CO, NO_x, VOCs, NH_3;
- **Concentrations** of GHGs, aerosols and chemically active gases;
- **Land-use/ land-cover data** (cropland, pasture, primary vegetation, secondary vegetation, forests).[2]

Annual land use information is provided as a consistent set of 0.5°×0.5° degree fractional coverage maps for the 1500-2100 period. For all reactive gases and aerosol precursor compounds, emissions are also gridded and reported at 0.5°×0.5° degrees. The emissions are also converted to concentrations using a carbon-cycle climate model MAGICC6 (Meinshausen et al., 2011a; Meinshausen et al., 2011b) for well-mixed GHGs, and an atmospheric chemistry model CAM3.5 (Gent et al., 2009) for reactive short-lived substances.

Overall, compared to the existing body of the literature, RCP8.5 can be considered as a representation of the high-range of non-climate-policy scenarios; RCP6 can be interpreted twofold (either a medium baseline or a high mitigation case); RCP4.5 broadly corresponds to intermediate mitigation scenario, while RCP2.6 is the scenario with the most stringent climate policy.

It should be emphasized that the Fifth phase of the Coupled Model Intercomparison Project (CMIP5) [3] that produced a state-of-the-art multimodel dataset designed to advance knowledge of climate variability and climate change (Taylor et al., 2012), the analysis of which underlied IPCC AR5 (IPCC, 2014), was essentially based on the RCP approach outlined in the present section.

2.3.2. Shared Socioeconomic Pathways (SSPs)

Pathways for radiative forcing (RCPs, see Sec. 2.3.1) should be combined with alternative pathways for socioeconomic development to conduct climate impacts/ adaptation/ mitigation research. The latter pathways are referred to as **Shared Socioeconomic Pathways (SSPs)** (O'Neill et al., 2014).

SSPs are defined as reference pathways describing plausible alternative development of society and ecosystems in the 21st century in the absence of climate change or climate policies.

The following key differences between SSPs and the previous generation of scenarios (SRES, Sec. 2.2) can be outlined (O'Neill et al., 2014):

- The base year data are updated;
- SSPs are better tailored for adaptation and impacts analysis than SRES;
- The 'two-dimensionality' of scenario uncertainty (related both to radiative forcing and to socioeconomics) is explicitly captured (see below the note on scenario matrix architecture);

[2] A more detailed specification of information available for RCPs is provided in Table 1, (van Vuuren et al., 2011).

[3] http://cmip-pcmdi.llnl.gov/cmip5/index.html?submenuheader=0

- SSPs are designed to be iterative and open for future developments.

Two versions of SSPs – basic vs. extended – should be distinguished.

SSPs are designed in a two-dimensional "challenges space" (in axes "Socioeconomic challenges for adaptation"/ "Socioeconomic challenges for mitigation") and include:

- **SSP1** – "Low challenges" – "Sustainability";
- **SSP2** – "Intermediate challenges" – "Middle of the Road";
- **SSP3** – "High challenges" – "Fragmentation";
- **SSP4** – "Adaptation challenges dominate" – "Inequality";
- **SSP5** – "Mitigation challenges dominate" – "Conventional development".

When combined, RCPs and SSPs jointly form the 4×5 scenario matrix (van Vuuren et al., 2014) with 4 rows (corresponding to 4 different RCPs) and 5 columns (corresponding to 5 different SSPs). Each cell in the scenario matrix represents possible scenarios that combine elements of adaptation and mitigation policies (note that *not* every cell of the scenario matrix needs to be populated).

The quantification of SSPs has been performed by several research groups. Particularly, for each SSP population projections (Samir KC et al., 2010; Lutz and Samir KC, 2011) and urbanization projections (Jiang and O'Neill, 2015) were developed. Alternative economic projections for GDP and GDP per capita were developed by three modelling teams: OECD (Chateau et al., 2012), PIK (Hawksworth, 2006) and IIASA (Cuaresma, 2015) groups, respectively.[4]

2.3.3. Shared climate Policy Assumptions (SPAs)

The RCP-SSP scenario matrix as described in Sec. 2.3.2 is two-dimensional. The third dimension is added with the development of a (small) number of **Shared climate Policy Assumptions (SPAs)** capturing key mitigation/ adaptation policy attributes like goals, instruments and obstacles (Kriegler et al., 2014).

Two types of SPAs should be distinguished: full SPAs and reduced SPAs. A full SPA includes all mitigation and adaptation policy targets, and therefore partially includes information from RCP and SSP dimensions of the scenario matrix (the non-orthogonality case). A reduced SPA excludes the mitigation/ adaptation policy goals already captured by RCPs and SSPs, therefore the reduced SPA axis is orthogonal to both RCP and SSP axes.

[4] SSP Database (Shared Socioeconomic Pathways), Version 1.0 is available at IIASA repository, URL: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about (accessed 08 November 2015).

3. Climate scenarios in COMPLEX WP5 modeling system

3.1. IAM – GCAM

The Global Change Assessment Model (GCAM) is a partial equilibrium model of the world with 32 regions. GCAM operates in 5 year time steps from 1990 to 2100 and is designed to examine long-term changes in the coupled energy, agriculture/land-use, and climate system. GCAM includes a 283-region agriculture land-use module and a reduced form carbon cycle and climate module in addition to its incorporation of demographics, resources, energy production and consumption. The clear linkages of the modules are shown on Figure 1.

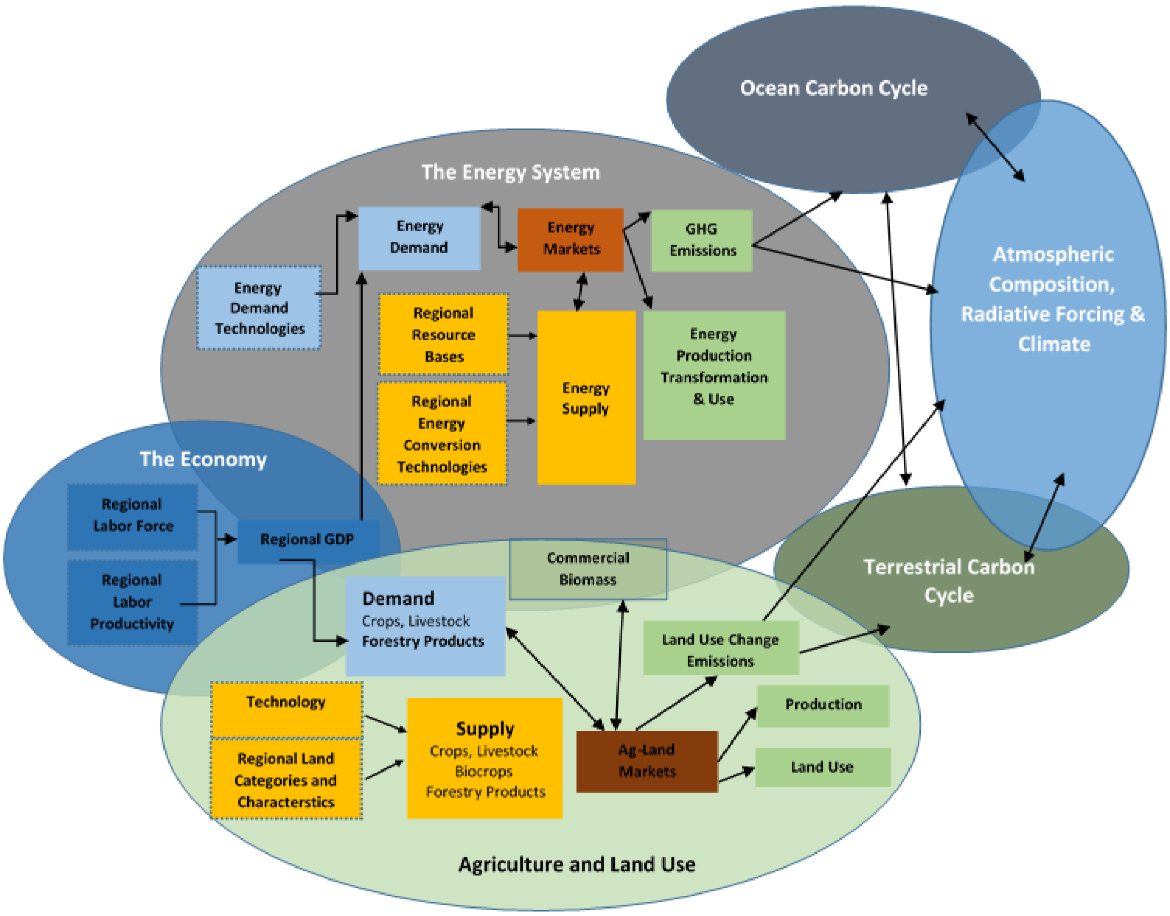

Figure 1: Linkages of GCAM modules

The Climate module: GCAM takes inputs from MAGICC 5.3 (Model of the Assessment of Greenhouse gas Induced Climate Change). MAGICC consists of the entire chain from emissions to concentrations to global radiative forcing to global changes in temperature and sea-level.

The first set of models within MAGICC 5.3 converts emissions to concentrations, and covers a wide range of greenhouse and pollutant gases. With the help of MAGICC 5.3, emissions of greenhouse gases, aerosols, and short-lived species are determined endogenously in GCAM, in other words, the emissions are linked to underlying human activities. Emissions mitigation for CO_2 is treated explicitly and endogenously for fossil fuel, industrial and land-use emissions in the GCAM. Emissions of non-CO_2 greenhouse gases, aerosols and short-lived species are also endogenously determined, emissions mitigation is modeled as a marginal abatement cost (MAC).

Global radiative forcing from well-mixed greenhouse gases is determined from concentration values using simple relationships drawn from the literature. Forcing from carbon dioxide is proportional to the natural logarithm of carbon dioxide concentrations, forcing from methane and nitrous oxide is proportional to the square root of concentrations (with an interaction term). Forcing from fluorinated gases is linear in concentration. Forcing from tropospheric ozone is estimated using non-linear relationships between emissions of methane and reactive gases NO_x, CO, and VOCs.

Direct and indirect forcing from aerosols is included. Direct forcing from sulfur dioxide (SO_2), black carbon (BC), and organic carbon (OC) are taken to be proportional to SO_2, BC, and OC emissions, respectively. The GCAM version of MAGICC has been updated to include a direct representation of BC and OC emissions provided by GCAM. In the distribution version of MAGICC, BC and OC forcing is, in contrast, inferred from proxy measures such as land-use change and SO_2 or CO emissions. Indirect cloud forcing in MAGICC is taken to be proportional to the natural logarithm of sulfur dioxide emissions.

Given total radiative forcing, global mean temperature change is calculated using an upwelling-diffusion model of ocean thermal response (with 40 ocean layers), together with a differential land/ocean forcing response. Climate calculations are performed with four boxes: two hemispheres plus land/ocean for each. Aerosol forcing is split into these four boxes as well. MAGICC uses its calculation of heat diffusion into the ocean to estimate sea-level rise (SLR) due to thermal expansion. SLR components due to melting of land glaciers and (optionally) large Arctic and Antarctic ice sheets are also included.

MAGICC has been shown to be able to emulate the global-mean results from most complex general circulation models (Raper et al., 1996). To produce the climate scenarios, GCAM allows the user to change specified parameters, including climate sensitivity, carbon-cycle, and aerosol forcing strength (Smith et al., 2006).

Climate damages are not calculated in GCAM explicitly as GCAM is a linear model following the conceptual scheme ***energy generation→ emissions→ temperature increase,*** which does not have feedback.

With GCAM it is possible to develop and test different policy scenarios. Some of the scenarios including the standard ones (such as RCPs, Sec. 2.3.1), carbon caps, carbon taxation etc. have already been developed.

3.2. SD – MADIAMS/SDEM

The MADIAMS model family, a substantial part of which has been / is being developed within EU FP7 COMPLEX project, currently includes, but is not limited to, the following models:

- The Multi-Actor Dynamic Integrated Assessment Model (MADIAM) (Weber et al., 2005);

- The Multi-Actor Dynamic Integrated Assessment Model System (MADIAMS) – a further development of MADIAM describing the out-of-equilibrium features of economic dynamics (Hasselmann and Kovalevsky, 2013);
- The Structural Dynamic Economic Model (SDEM) – a stylized prototype of MADIAMS (see more detail in Sec. 4 below);
- A family of models exploring the win-win framework of climate mitigation policies and the benefits of green investment at a national scale (Hasselmann, 2013);
- A set of regionally resolved models to explore the potential interregional welfare redistribution impacts of carbon taxes (Kovalevsky and Hasselmann, 2014d);
- The 'Arctic feedback' model evaluating the potential effects of shrinking Arctic sea ice on the global economy (Kovalevsky and Hasselmann, 2014c);
- The North-South Euro crisis model (Hasselmann et al., 2015);
- Other models (e.g. (Hasselmann and Voinov, 2011; Kovalevsky and Hasselmann, 2014a)).

The main members of MADIAMS model family are global-scale system dynamics Integrated Assessment models (IAMs) designed within a classical IAM conceptual scheme presented on Figure 2.

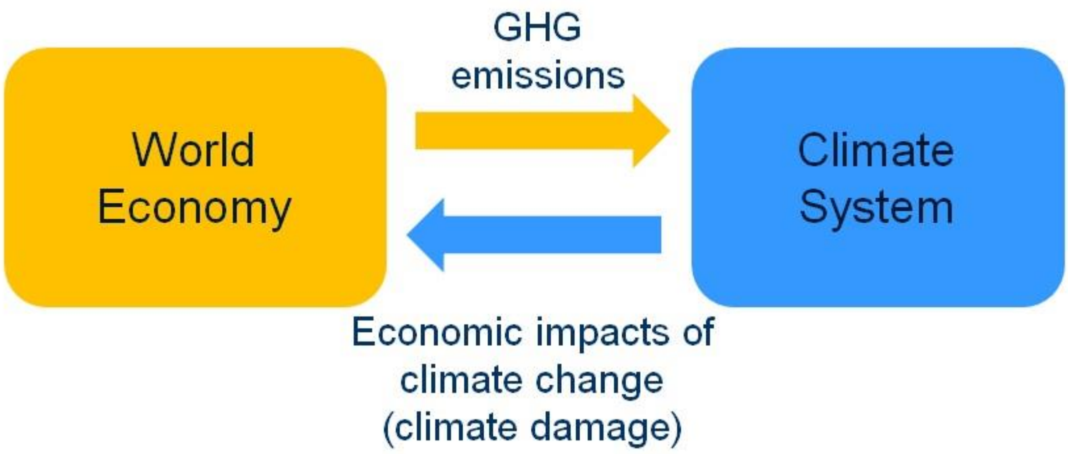

Figure 2: A conceptual scheme of Integrated Assessment modeling (IAM), also applicable to members of MADIAMS/SDEM model family

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 GHG emissions (represented in 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 dynamics (including the dynamics of carbon emissions) are computed self-consistently. This means that climate scenarios in general and carbon emission scenarios in particular are products of the MADIAMS model simulations themselves, and in this respect there is no need to incorporate in the modelling framework any external ('exogenous') quantitative emissions/ climate scenarios like RCPs (Sec. 2.3.1) or SRES (Sec. 2.2) (although, of course, the results of MADIAMS model runs are compared with existing scenarios).[5]

Carbon emissions are computed in MADIAMS by converting the output of modeled sectors of the economy (specified by relevant production functions, usually of Leontieff 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 can be linked to different climate modules. For instance, in the initial version of MADIAM (Weber et al., 2005) the carbon cycle – climate model NICCS (Hooss et al., 2001) was incorporated. Several later versions of MADIAMS/SDEM include the climate module as described in (Kellie-Smith and Cox, 2011). For further details on climate modules used in the recent versions of SDEM see Sec. 4.1 below.

The developed versions of models have been run with several alternative climate damage functions. In the initial version of MADIAM (Weber et al., 2005) a climate damage function with quadratic dependence both on global mean surface air temperature increase above the pre-industrial level and on the rate of its change (Hasselmann et al., 1997) was utilized:

$$\delta = Dy\left\{\left(\frac{\Delta T}{T_{\mathrm{b}}}\right)^2 + \left(\frac{d\Delta T/dt}{dT_{\mathrm{b}}/dt}\right)^2\right\} \tag{1}$$

where δ is the (per capita) climate damage, y is the (per capita) output, T_{b} is a benchmark temperature, dT_{b}/dt is a benchmark rate of change of temperature and D is a benchmark coefficient relating mean (tangible) climate damages to GDP. The recent versions of SDEM have been run e.g. with Nordhaus and Weitzman climate damage functions (see Sec. 4.2 below).

3.3. CGE – EXIOMOD

3.3.1. General description of EXIOMOD

EXIOMOD is a computable general equilibrium (CGE) model. The unique database of the EXIOMOD model, EXIOBASE, comes from two European projects: EU FP6 EXIOPOL and EU FP7 CREEA. EXIOBASE is a global, detailed Multi-Regional Environmentally Extended

[5] It should be noted in this respect that both SRES scenarios (Sec. 2.2) and RCPs (Sec. 2.3.1) were developed as outcomes of several IAMs exactly within the paradigm of self-consistent computation of coupled climate-socioeconomic dynamics described in the current section (and utilized in MADIAMS as well).

Supply and Use / Input Output (MR EE SUT/IOT) database. The international input-output table can be used for the analysis of the environmental impacts associated with the final consumption of product groups. EXIOBASE 2.0 has a unique level of detail and covers 30 emissions around resource extractions, given specifically for 164 sectors and products by 43 countries that make up 95% of global GDP, plus the Rest of the World.

The EXIOMOD model, with its extensive representation of production structure of the world economy, variation of consumption patterns among social classes and environmental extensions, allows for a wide range of scenarios studies and policy-oriented analysis. Possible policy-oriented applications with EXIOMOD include assessment of environmental, social, and economic impacts of energy, climate change and resource efficiency policies on the EU and world-wide scales:

1. Social effects: includes the representation of three education levels, ten occupation types and households grouped into five income classes. One can trace the effects of specific policy on income redistribution and unemployment.
2. Economic effects: the model captures both direct and indirect (wide-economic and rebound) effects of policy measures. It allows for calculation of detailed sector-level impacts at the level of 164 economic sectors.
3. Environmental effects: the model includes representation of all GHG and non-GHG emissions, different types of waste, land use and use of material resources.

3.3.2. Energy, environment and welfare analysis in EXIOMOD

All production and consumption activities in the EXIOMOD model are associated with emissions and environmental damage. This is in particular true for the transportation. The model incorporates the representation of all major GHG and non-GHG emissions. Emissions in the EXIOMOD model are associated either with the use of different energy types by firms and households or with the overall level of the firms' output.

The EXIOMOD model includes the following types of emissions: nitrous oxide (N_2O), mono-nitrogen oxides (NO_x), hexachlorobenzene (HCB), carbon dioxide (CO_2), lead (Pb), mercury (Hg), Nickel (Ni), Copper (Cu), Arsenic (As), indeno(1,2,3-cd)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, cadmium (Cd), zinc (Zn), Benzo(a)pyrene, carbon monoxide (CO), sulfur oxides (SO_x), methane (CH_4), ammonia (NH_3), selenium (Se), chromium (Cr), dioxins, non-methane volatile organic compounds (NMVOC), polycyclic aromatic hydrocarbon (PAH), polychlorinated biphenyl (PBCs), particulates (PM10, PM2.5), trisodium phosphate (TSP).

Emissions are measured in tones of CO_2 equivalent and are modeled as the fixed shares of production energy inputs of households' energy consumption.

Environmental quality is one of the main factors in measuring households' utility levels. Changes in the levels of emissions have a direct impact upon the utilities of the households. Different income classes in the model are influenced differently by the changes in emission levels of local pollutants. Each emission type represented in the model is associated with the monetary value. The overall monetary value of emissions in the economy is equal to emissions of the households and emissions of the firms. The monetary evaluation of emissions by each household group depends on its willingness-to-pay. It is assumed that the willingness-to-pay is closely correlated with the income of the household. Rich households put a higher value to the emissions than the poor ones. When income-specific monetary coefficients are introduced, the welfare of each of the five population categories in the EXIOMOD model can be calculated with the environmental quality incorporated in an additive way.

3.3.3. Calculation of emissions

EXIOBASE 2.2 provides information about emissions in the form of environmental extensions. GHG emissions are represented separately per substance for each industry and for households, additionally information is available on how much emissions occurred due to fuel combustion and how much due to other production processes. In order to be able to calculate emissions in a baseline or for a policy simulation, the emission coefficients are utilized. For the calibration year for each type of substance two types of emission coefficients are calculated (per industry and for households):

1) Combustion: kg of emissions per euro of combustible energy use.
2) Non-combustion: kg of emissions per euro of output.

For future periods monetary values for use of combustible energy and output are defined by the solution of EXIOMOD. New emission values are calculated by multiplication of new monetary values with emission coefficients. In case information is available, exogenous trend can be overlaid on top of the calibrated emission coefficients, e.g. due to technological progress.

3.3.4. Climate module. Climate impacts. Climate damages

Yearly emissions from EXIOMOD are used as inputs for the climate module in FUND model[6] (Anthoff and Tol, 2013). FUND computes atmospheric concentrations of carbon dioxide, methane, nitrous oxide and Sulphur hexafluoride, from which radiative forcing, global mean temperature, and sea level rise are derived.

The climate impact module in FUND includes the following impact categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, energy consumption, water resources, unmanaged ecosystems, diarrhoea, and tropical and extra tropical storms. In addition, climate change affects population growth through premature deaths or migration due to sea level rise. Impact functions are calibrated to the results of economic impact models reported in the literature, and all climate impacts are monetized. Climate impacts from FUND are used to calculate regional reductions in labor supply and sectoral reductions in capital stock in EXIOMOD 2.0. One particular challenge lies in mapping specific climate impacts from FUND to the sectoral structure of EXIOBASE. For certain impacts, conversion of impacts is fairly straightforward (e.g., agriculture, forestry, population growth, reductions in labor productivity due to illness, energy consumption), while in other cases (e.g., water resources, tropical and extra tropical storms) mapping will have to be based on observations from the literature.

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[6] http://www.fund-model.org/

In EU FP7 COMPLEX, the EXIOMOD team aims to use the qualitative narratives of the SSP scenarios (Sec. 2.3.2) which will be used in conjunction with the RCPs (Sec. 2.3.1).

3.4. ABM

The monetary cost of climate change is now expected to be higher than many earlier studies suggested, because those studies tended not to include some of the most uncertain but potentially most damaging impacts. Meanwhile modeling the monetary impacts of climate change globally is very challenging: it requires quantitative analysis of a very broad range of environmental, economic and social issues (Stern, 2007). Moreover, in real climate-human system, there will be feedbacks among many links in the chain (Helm, 2005).

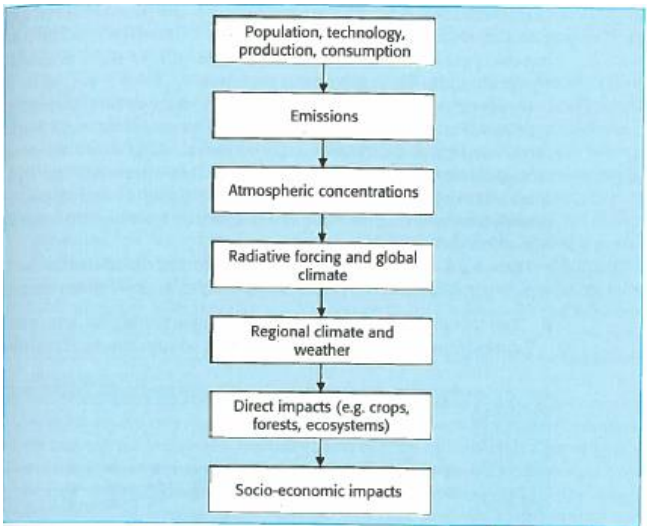

Figure 3: Modelling climate change from emissions to impact (Helm, 2005)

Many scientists have contributed to the understanding of natural process of climate change and the impact of energy-economy systems on climatic system. Driven by the growing consensus over scientific basis of man-made climate change, the climate-energy-economy (CEE) challenges have become a public policy priority. To be able to formulate an appropriate energy policy for complex adaptive CEE systems, policymakers should ideally have decision support tools that are able to explore non-marginal changes in energy markets over the coming decades to plan ahead accordingly.

It is widely accepted that climatic system is likely to react abruptly and shift suddenly to a different state after a certain threshold of CO_2 concentrations is reached (Stern, 2007; Lohmann, 2011; Rial et al., 2004; Stocker, 1999). Economic systems are also likely to undergo non-marginal changes. There is no reason to assume that our behavior, and in particular our economic choices on the energy consumption and production will remain the same. Therefore, one needs to quantitatively explore and trace non-marginal changes in energy markets to be able to design robust economic, energy and climate mitigation policies. Many economic macro models, that assume rational representative agent with static behavior, are designed to study marginal changes only. So there is a need for models that are able to capture non-linear changes and their emergence (Stern, 2013).

Within the EU FP7 COMPLEX project an ABM of the energy market plays a vital role within the coupled suit of models complementing macro-economic and climatic models. The demand side of the ABM is represented by heterogeneous households with different preferences, awareness of climate change, and socio-economic characteristics. Meanwhile, the microeconomic dynamics on the supply side could include the diffusion of alternative energy technologies. The quantities and prices of various energy sources and corresponding greenhouse gas emissions resulting from the microeconomic choices are some of the indicators (outputs) of an aggregated ABM market dynamics (Niamir and Filatova, 2015a).

The agent-based energy market model aims to investigate households climate awareness, e.g. their preference in switching to low-carbon energies, and their CO_2 footprints via different climate, socio-economic scenarios on the demand side. These preferences for low carbon vs. fossil fuel energy sources (γ) are formalized in a households' utility function (see Eq. (2)) and their expectations. A state of the environment – or climate (C) – may enter the utility function as well. In this case the state of the climate is exogenous to the ABM as changes in climate are global processes and cannot be modeled with NUTS2 ABM. In addition to this, cumulative changes in households' CO_2 footprints modeled with ABM on NUTS2 scale may be aggregated to the changes in CO_2 patterns for a whole country via CGE. This may serve as inputs to climate modules of the integrated modeling suite. The ABM may also quantify the effects of low-carbon technology diffusion and energy production on CO_2 emissions on the supply side of an energy market (Niamir and Filatova, 2015b).

$$U = z^{\alpha} E^{1-\alpha} C^{\gamma} . \qquad (2)$$

ABM will be run under different scenarios, which potentially could include: (i) different socio-climatic awareness and decisions (potentially coming from a survey), (ii) various climate mitigation or energy-related policies.

4. Endogenous generation of climate scenarios in SD models: an example of MADIAMS/SDEM

4.1. SDEM: brief model description

The Structural Dynamic Economic Model (SDEM), a stylized prototype of MADIAMS, was initially developed by Barth (2003) in a dynamic optimization mode, i.e. following the paradigm of intertemporal optimization typical for mainstream IAMs. Later several alternative versions of SDEM have been developed, primarily in system dynamics mode, but occasionally also in the optimization mode (Kovalevsky, 2014a; Kovalevsky, 2014b; Kovalevsky, 2016, in press). Below one of the system dynamics versions of SDEM developed within EU FP7 COMPLEX and reported in (Kovalevsky and Hasselmann, 2014b) is briefly described.

The version of SDEM presented in (Kovalevsky and Hasselmann, 2014b) 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, the two 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 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 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. As mentioned above, no utility maximization/ intertemporal optimization procedures are assumed in the 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.

The climate module is adopted from (Kellie-Smith and Cox, 2011) and consists of dynamic equations for CO_2 concentration and for global mean surface air temperature T. For abrupt climate change simulations (see Sec. 4.3 below) a four-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.

4.2. Gradual climate change scenarios

Generally, 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 mitigation policies) and for five alternative global carbon tax rates (10, 20, 30, 40, and 50 USD/tCO_2), have been performed assuming two alternative specifications of the climate damage function: the quadratic function

$$1 - d_N(T) = \frac{1}{1 + 0.0028(\Delta T)^2} \qquad (3)$$

where ΔT is the temperature increase above the pre-industrial level, proposed by Nordhaus (2008) for DICE model, and widely used later by other authors, and a strongly nonlinear function

$$1-d_W(T)=\frac{1}{1+(\Delta T/20.46)^2+(\Delta T/6.081)^{6.754}} \quad (4)$$

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 for gradual climate change conditions, i.e. computed with the SDEM model using the climate module adopted from (Kellie-Smith and Cox, 2011) (no Atlantic THC module) are presented on Figure 4 (global mean temperature) and Figure 5 (effective GWP, i.e. Gross World Product, reduced through climate damage) for the Weitzman climate damage function (Eq. (4)). Figure 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, Figure 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 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).

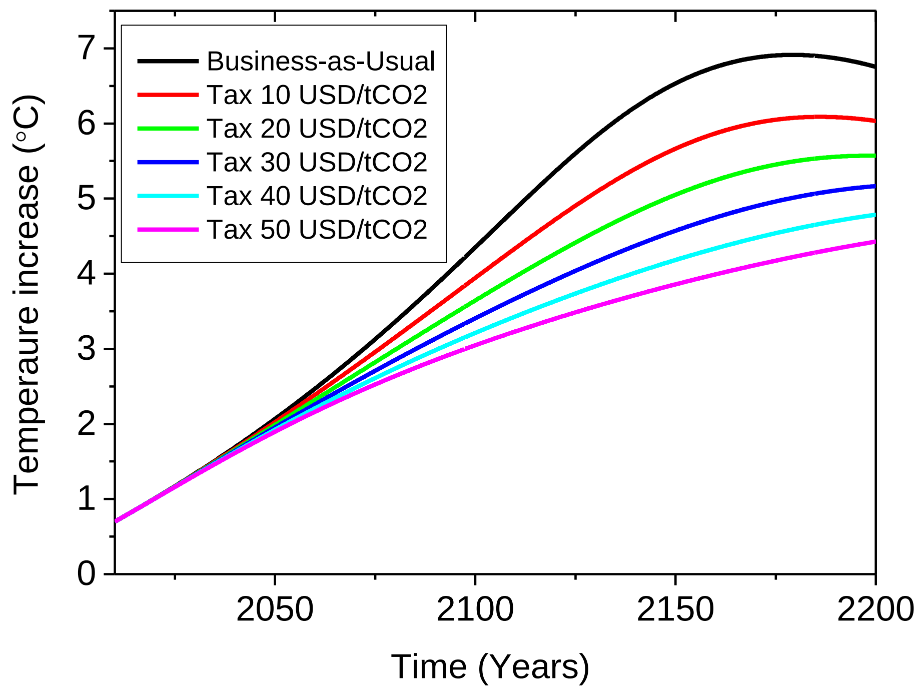

Figure 4: Global mean surface air temperature increase above pre-industrial level projected by SDEM for a business-as-usual scenario and five alternative mitigation scenarios assuming different global carbon tax rates (Kovalevsky and Hasselmann, 2014b)

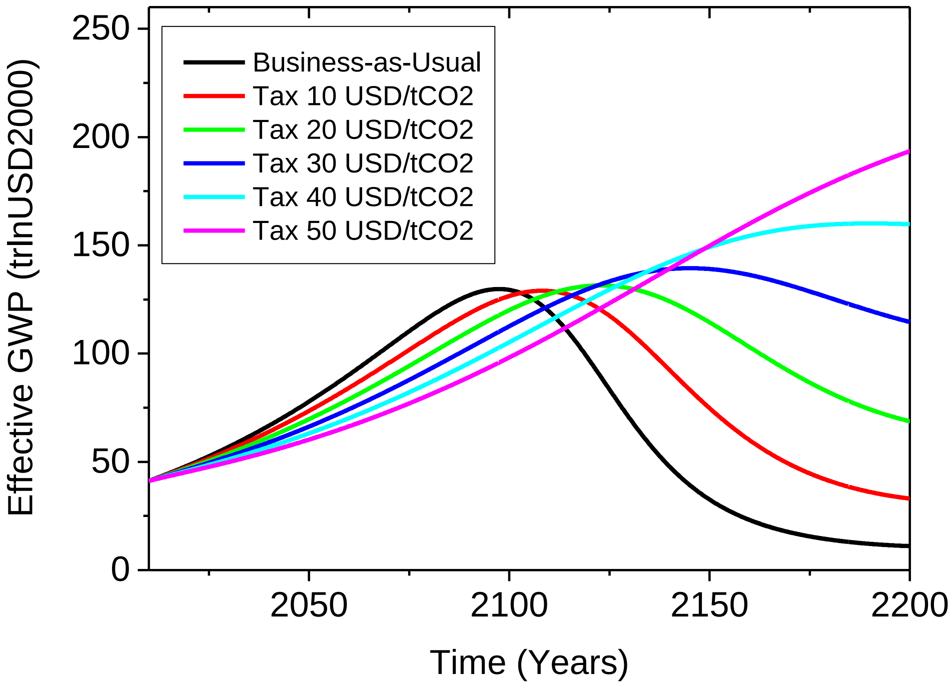

Figure 5: Effective GWP (corrected for climate damage) projected by SDEM for the business-as-usual scenario and five alternative mitigation scenarios with different global carbon tax rates (Kovalevsky and Hasselmann, 2014b)

4.3. Abrupt climate change scenarios (possible shutdown of Atlantic thermohaline circulation)

Figure 6 shows the SDEM simulations under abrupt climate change conditions. The model runs are made until the end of the 23rd century using the climate module adopted from (Kellie-Smith and Cox, 2011) and 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). Note that no additional climate damages arising from possible abrupt climate change have been introduced into the climate damage function (as opposed to what has been 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.

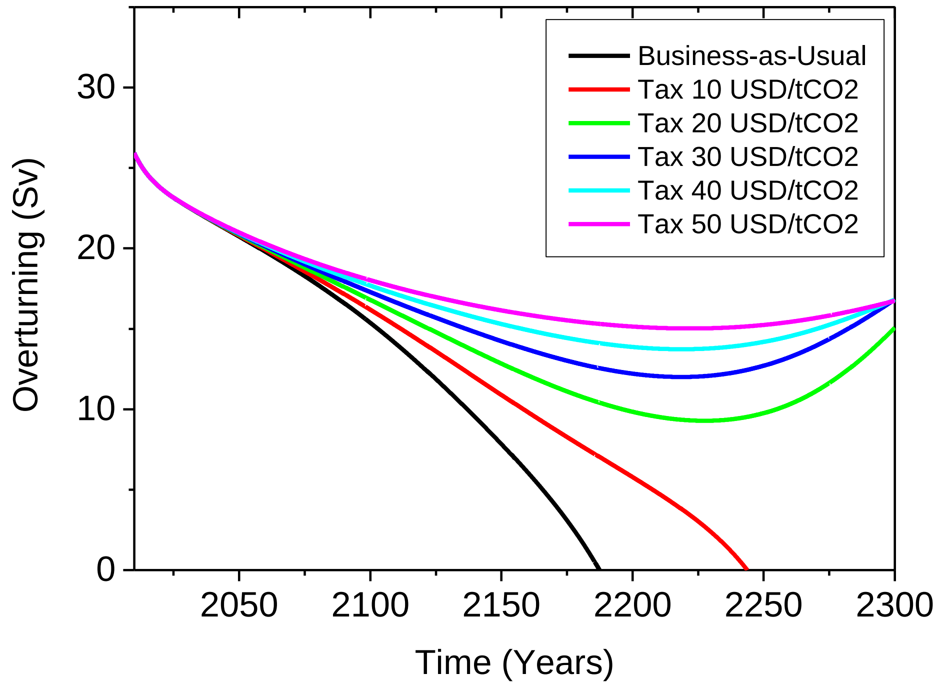

Figure 6: Strength of Atlantic thermohaline overturning circulation, projected by SDEM for the business-as-usual scenario and five alternative mitigation scenarios corresponding to different global carbon tax rates (Kovalevsky and Hasselmann, 2014b)

5. Conclusions and outlook

Over time, standard climate scenarios broadly used in mitigation and adaptation research have evolved from stylized representations of potential future increases of atmospheric CO_2 concentrations (used as forcing in climate models) to well-elaborated alternative narratives/ storylines of possible futures of climate-energy-economic system supplemented by detailed quantitative datasets. The latest generation of scenarios (RCPs/SSPs/SPAs) used for preparation of IPCC AR5 (IPCC, 2014) has been already incorporated in some members of EU FP7 COMPLEX modeling system, and will be compared with the outcomes of other COMPLEX models in the near future.

The EU FP7 COMPLEX modeling system consists of models of different degrees of complexity based on different modeling approaches and paradigms. Moreover, different models describe different aspects of the dynamics of coupled climate-energy-economic system at different spatial scales, i.e. they are designed to address different research questions. As a consequence of adopted diverse approaches to model design, the definition of climate scenario, as clearly seen from this report, also varies from one model to another. Thus, one can say the COMPLEX modelling system operates with a system of climate scenarios. This multi-facet approach helps tackling a broad spectrum of research questions relevant to climate mitigation/ adaptation problem and assessing the efficiency of potential mitigation and adaptation options more comprehensively.

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