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Integrated assessment model of society-biosphere-climate-economy-energy system

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ABSTRACT

The feedback based integrated assessment model ANEMI_2 represents the society-biosphere-climate-economy-energy system of the earth and biosphere. The ANEMI_2 model is based on the system dynamics simulation approach that (a) allows for the understanding and modeling of complex global change and (b) assists in the investigation of possible policy options for mitigating, and/or adapting to changing global conditions within an integrated assessment modeling framework. This paper outlines the ANEMI_2 model and its nine system components: climate, carbon cycle, land-use, population, food production, hydrologic cycle, water demand, water quality, and energy-economy. To evaluate market and nonmarket costs and benefits of climate change, the ANEMI_2 model integrates an economic optimization approach, with a focus on the international energy stock and fuel price, climate interrelations and temperature change. The model takes into account all major greenhouse gases (GHG) influencing global temperature and sea-level variation. Results from several scenarios (a) compare well with other information available in the scientific literature, (b) present comprehensive response of the society-biosphere-climate-economy-energy system to the selected scenarios, and (c) confirm the support role of the ANEMI_2 model in the policy development and analyses.

Software availability

The ANEMI model code and data used in this study are available in Akhtar (2011). The model is available for further research use upon request (simonovic@uwo.ca).

1. Introduction

The earth's climates have changed in the past and will change in the future. Climate change has been a subject of research interest for many years and the attention has been growing with the awareness of relationship between climate change and socio-economic dynamics. Although there exists considerable knowledge of the broad characteristics of the climate, there is still need for improved understanding of how the major processes of climate change – of the world's oceans, ice masses, exposed land surface and socio-economic processes – interact.

Integrated assessment modeling, supported by the improvement of computer technology, surfaced in the mid-1980s as a new paradigm for interfacing science and policy concerning complex environmental issues such as climate change. According to Parson (1994): "To make rational, informed social decisions on such complex, long-term, uncertain issues as global climate change, the capacity to integrate, reconcile, organize, and communicate knowledge across domains – to do integrated assessment – is essential." Therefore, integrated assessment models are believed to produce insights that cannot be easily derived from the individual natural or social science component models that have been developed in the past (Laniak et al., 2013; Weyant, 1994).

ANEMI modeling effort at the University of Western Ontario, Canada uses a system dynamics simulation approach for integrated assessment of climate change impacts (Davies and Simonovic, 2010, 2011). The ANEMI_2[1] model, presented in this paper, represents the society-biosphere-climate-economy-energy system on a global scale (Akhtar, 2011; Akhtar et al., 2011). To evaluate market and nonmarket

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[1] ANEMI_2 is an integrated assessment model consisting of nine system components: climate, carbon cycle, energy-economy, land-use, food production, population, hydrologic cycle, water demand, and water quality.

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costs and benefits of climate change, the ANEMI_2 model integrates an economic approach, with a focus on the international energy stock and fuel price, with climate interrelations and temperature change. The model takes into account all major greenhouse gases (GHG) influencing global temperature and sea-level variation. Several of the model system components are build upon the basic structure of the ANEMI_1 model developed by Davies (2007). The ANEMI_2 model extends the system dynamics simulation approach by integrating it with an optimization algorithm capable of describing the energy-based economic activities that affect long-term Earth-system behavior. Experimentation with different policy scenarios demonstrates the consequences of these activities on future behavior of the society-biosphere-climate-economy-energy system through feedback based interactions. The use of the ANEMI_2 model improves both, the scientific understanding of the complex global system and the socio-economic policy development (Akhtar, 2011). This paper describes the ANEMI_2 model structure in detail and illustrates its use through the analyses of three global policy scenarios.

Section 2 of the paper summarizes the different modeling approaches used in the development of ANEMI_2 model. The following section (Section 3) provides a brief description of the model's individual system components. Section 4 describes the experimentation undertaken to analyze three policy scenario associated with water resources use, carbon tax introduction, and change in land use. Section 5 summarizes and evaluates the significant results of model simulations against research objectives. The paper ends with recommendations for future research.

2. Model of the society-biosphere-climate-economy-energy system

> *"Climate change is expected to exacerbate current stresses on water resources.[…] Widespread mass losses from glaciers and reductions in snow cover over recent decades are projected to accelerate through the 21st century, reducing water availability, hydropower potential, and changing seasonality of flows [in some regions]."*
>
> Intergovernmental Panel on Climate Change, (2007a).

Climate system modeling with General Climate Models (GCMs) is currently the best choice for analyzing the physical climate system. However, the climate system modeling has been evolving towards Earth system modeling by considering dynamics and complexity of atmosphere, oceans, land surface, and biosphere (Jacobson et al., 2008). In spite of this scope, the earth system modeling abstracts from socio-economic forces, which are the main driving forces behind rapid climate change. Therefore the integrated assessment modeling (IAM) provides a convenient framework for combining knowledge from a wide range of disciplines.

Climate change economics are largely developed using the general equilibrium theory of Arrow and Debreu (Shafer and Sonnenschein, 1975). This approach utilizes optimization methods to characterize the supply and demand functions for energy and system components output. The other model system components use system dynamics based simulation that allows a very detailed mathematical representation of each component, such as WaterGAP2 (Alcomo et al., 2003). Hence integration of optimization and system dynamics simulation is carried out under the integrated assessment modeling framework in the development of ANEMI_2 model (Akhtar, 2011).

2.1. Integrated assessment modeling

IAMs available today (DICE, AIM, MERGE, ICAM, FREE, MESSAGE, IMAGE and so on) are used in (i) policy optimization (such as DICE, which seeks optimal policy strategies) and (ii) policy evaluation (such as IMAGE, which assesses specific policies). Optimization models are normative in character and typically analyze climate change from an economic perspective, i.e., they focus on the efficiency and rationality of a policy (Tol and Fankhauser, 1998). The level of optimization modeling details makes the optimization algorithm unmanageable. Due to computational limitations, optimization models tend to be based on compact representations (high degree of generalization) of both the socio-economic and natural science system components. They thus contain a relatively small number of equations, with a limited geographic coverage. Policy evaluation models tend to be descriptive and contain much more details describing physical, economic and/or social system components. These models are often referred to as simulation models, and are designed to calculate the consequences of specific climate policy strategies in terms of a suite of environmental, economic, and social performance measures.

Over the past decade or so, IAMs have been widely utilized to analyze the interactions between human activities and the global climate (Laniak et al., 2013; Weyant et al., 1996). They are usually comprehensive, but produce less detailed models than the conventional climate- or socio-economic-centred modeling. As Rotmans et al. (1997b: 36) note, IAMs "are meant to frame issues and provide a context for debate. They analyze problems from a broad, synoptic perspective." It is a system-wide approach, where one tries to look at various components of a system as a whole. However, it is always an issue to sacrifice between representing depth in individual system components and representing breadth of the overall system (Kelly et al., 2013). Therefore the challenge to integrated assessment modeling is to capture the sufficient depth of individual system components without compromising breadth of the overall system.

The first IPCC report referenced two IAMs, the Atmospheric Stabilization Framework developed by the US Environmental Protection Agency (EPA) and the Integrated Model for the Assessment of the Greenhouse Effect (IMAGE) model (Rotmans, 1990; Van Vuuren et al., 2006). These were employed to assess the factors controlling the emissions and concentrations of GHGs over the next century. The MAGICC model was subsequently developed to incorporate ocean heat transport and a carbon cycle component to capture land-use change (Meinshausen et al., 2008). A regional Integrated Assessment Tool (RIAT) is recently developed by Carnevale et al. (2012) to assess air quality. It implements a multi-objective problem for the selection of effective policies to control pollution exposure to primary and secondary pollutants. Davies (2007) provides some examples of integrated assessment models including the Integrated Model to Assess the Greenhouse Effect, IMAGE 2.0 (Alcamo, 1994), the Asian Pacific Integrated Model, AIM (Matsuoka et al., 1995), the Model for Evaluating Regional and Global Effects of GHG reduction policies, MERGE (Manne et al., 1995), the Tool to Assess Regional and Global Environmental and health Targets for Sustainability, TARGETS (Rotmans and de Vries, 1997), the Integrated Global System Model, IGSM (Prinn et al., 1999), Integrated Climate Assessment Model, ICAM (Dowlatabadi, 2000), the Dynamics Integrated Climate-Economy model, DICE (Nordhaus and Boyer, 2000), the Feedback-Rich Energy-Economy model, FREE (Fiddaman, 1997, 2002), and World3 (Meadows et al., 2004). Because of their significant flexibility the IAMs are also been extensively used for agricultural system policy impact assessment to climate change (Bland, 1990; Van Ittersum et al., 2008; Ewert et al., 2009; Lehtonen et al., 2010).

Following the development path of IAMs, a circular references or "feedbacks" based model ANEMI_1 was introduced in 2007 and underwent a moderate modification in 2009 with the addition of energy system component (Davies, 2007; Davies and Simonovic,