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Methods and approaches to modelling the Anthropocene

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ABSTRACT

The 'Anthropocene' concept provides a conceptual framework that encapsulates the current global situation in which society has an ever-greater dominating influence on Earth System functioning. Simulation models used to understand earth system dynamics provide early warning, scenario analysis and evaluation of environmental management and policies. This paper aims to assess the extent to which current models represent the Anthropocene and suggest ways forward. Current models do not fully reflect the typical characteristics of the Anthropocene, such as societal influences and interactions with natural processes, feedbacks and system dynamics, tele-connections, tipping points, thresholds and regime shifts. Based on an analysis of current model representations of Anthropocene dynamics, we identify ways to enhance the role of modeling tools to better help us understand Anthropocene dynamics and address sustainability issues arising from them. To explore sustainable futures ('safe and operating spaces'), social processes and anthropogenic drivers of biophysical processes must be incorporated, to allow for a spectrum of potential impacts and responses at different societal levels. In this context, model development can play a major role in reconciling the different epistemologies of the disciplines that need to collaborate to capture changes in the functioning of socio-ecological systems. Feedbacks between system functioning and underlying endogenous drivers should be represented, rather than assuming the drivers to be exogenous to the modelled system or stationary in time and space. While global scale assessments are important, the global scale dynamics need to be connected to local realities and vice versa. The diversity of stakeholders and potential questions requires a diversification of models, avoiding the convergence towards single models that are able to answer a wide range of questions, but without sufficient specificity. The novel concept of the Anthropocene can help to develop innovative model representations and model architectures that are better suited to assist in designing sustainable solutions targeted at the users of the models and model results.

1. Introduction

The passage into the 21st century witnessed much debate and reflection on the relationship between humanity and the earth system. Most influentially, Crutzen and Stoermer (2000) argued that the cumulative effect of human activities on planetary scale processes has become so large as to warrant a new geological epoch. They suggested that the rise in greenhouse gases observed in ice cores from the start of the industrial revolution, some 250 years ago, heralded the start of the Anthropocene. The implication – that humanity was exerting an impact on ecosystems, ecological processes and biogeochemical cycles at planetary scales – focused attention on global environmental change research, particularly the scientific frameworks that would enable engagement with the growing complexity of interactions and feedback mechanisms. One conclusion was that appropriate policy and decision-making demanded much higher levels of scientific

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understanding, assessment and modelling if future human-environment interactions are to be anticipated correctly.

The implications of the Anthropocene concept reach far beyond the definition of a recent geological epoch characterized by human impacts on biogeochemical and biophysical processes. The Earth System perspective demands an understanding of both the system and human-derived forces and impacts on planetary processes. The Anthropocene essentially defines the growth of nested social-ecological systems where human-environment interactions are not only bi-directional but reach across different space and time scales. In this sense, the relevance of complexity science to a new understanding of human-environment interactions becomes apparent. The turn of the century also saw the International-Geosphere-Biosphere Programme (IGBP) community propose a 'second Copernican revolution' in our understanding of the Earth System (Schellnhuber, 1999), drawing upon complexity science to argue for a new generation of intermediate complexity simulation models that could simulate coupled human-environment relationships. The Amsterdam Declaration in 2001 extended these ideas to include the possibilities of threshold-dependent changes and tipping points (Moore et al., 2001). As IGBP and the GEC programs transition into the Future Earth program these ideas/foundations now advance to extend the inclusion of social dynamics and new forms of collaboration with model users and stakeholders.

The first model formulation at the scale of the Anthropocene and its interpretation are now over 40 years old with World3 and Limits to Growth, sponsored by the Club of Rome (Meadows et al., 1972) based on systems dynamics models of the Earth system developed by Forrester (1971). Despite the simplification of key global elements, these models embedded a large number of feedback loops in order to attempt useful simulations of human-environment interactions over many decades. World3 was used to explore different scenarios and how such scenarios differ giving different assumptions, rather than produce a particular prediction. At the time of publication, the World3 model was subjected to pointed critique (Cole, 1974). Yet the 'reference run' of World3 has been shown to produce a reasonably good fit to the empirical data since 1972 (Turner, 2008). World3 results highlight the growing risk of environmental degradation impacting catastrophically on the global population by the mid-21st century. Since the 1970s, there have been tremendous leaps in our understanding of biophysical aspects of the Earth system, some of which have come as a result of our ability to employ numerical methods on high performance computing platforms. As a result, several large integrated assessment models for global sustainability were developed and used to inform major science-policy reports (Hu et al., 2012; Meller et al., 2015; Schmitz et al., 2012). These modelling efforts underline the importance of dynamism and complexity as a defining property of the Anthropocene.

Unprecedented rates of change, complex interactions and new boundary conditions produce new challenges for managing contemporary social-ecological systems. Not least, static indicators of environmental change are now accepted as insufficient to understand the impacts of changing conditions (Jackson et al., 2009). Modelling the dynamical relationships between social, and environmental phenomena is increasingly demanded as part of the evidence base for making appropriate management decisions. We now have the challenge of moving from science-discovery questions to solution-driven questions; from questions related to the functioning of specific systems (process-response relationships, thresholds, tipping points, early warning signals and connectivity), to questions related to management (adapting to future climate change, identifying the unintended consequences of specific actions, or maximizing social-ecological resilience). The management questions can often only be answered through models that successfully capture, and develop from, the former science-discovery questions. Models that combine both are conceptually and technically difficult to develop, and there remains a tendency towards models designed to address management concerns while ignoring feedbacks, thresholds and spill-over effects (Maestre Andrés et al., 2012; Nicholson et al., 2009) or the inverse, models describing the socio-ecological dynamics without any direct relevance to decision-making or management.

There are many roles both for science and management driven models, for example, participatory and learning tools, ex-ante assessment of alternative actions, predictions and projections, and solution-oriented use. Since 1988, the Intergovernmental Panel on Climate Change has arguably done more than any other organization to instil in the minds of non-scientists the potential for science to project likely environmental conditions over several decades. Despite the current political or anti-science impasse, global climate models have provided key information to public or political debates for at least 20 years. The result is a widespread view that similar integrated and scenario-driven models for coupled social-ecological systems could also be readily available to aid decision-making. Associated problems of parameterizing social dynamics, such as individual behaviour, governance and macro-economic shifts, are profound and probably intractable over the near future (Silver 2012). Complex dynamical systems are inherently unpredictable—especially when they include humans. At the same time, the ability of a model to simulate reality, and provide consistent output results remains a key goal if Anthropocene models are to be useful.

This paper aims to assess the extent to which current models represent the Anthropocene. If humans have become important drivers of Earth system processes then how can we develop a new generation of models that put behaviour and social processes into the machine? How can we avoid models of models that we can no longer understand, or interrogate, or trust? What are the appropriate levels of abstraction and representation given the questions we seek to address? The paper begins with a description of the different uses of models in science-discovery and in the practice of policy formulation and environmental management. Based on the needs of the Anthropocene we next critically review the strengths and limitations of current models. Then we identify ways to better adapt our models to the issues identified and advance on the one hand the relationship between modellers and the users of models, and on the other the technical/design aspects of models.

This article is part of a special issue of Global Environmental Change on "the Anthropocene". The special issue represents a collaborative effort between the International Geosphere Biosphere Program (IGBP) and International Human Dimensions Program (IHDP) to develop an integrated natural and social science perspective of the Anthropocene. Thus, these articles provide forward-looking syntheses aiming at informing socio-ecological systems research on global change and the Future Earth program.

2. Uses of models and simulations

A multitude of models are available that represent aspects of global environmental change. Models differ in scope, purpose and structure. Most models are designed in response to either a science question or a management question, to address a specific spatial and temporal scale and consider varying aspects of the Earth System as exogenous to the model representation. In terms of purpose, such models offer us a simplified understanding of complex system functioning, extending our capacity to study system dynamics. In this perspective, models provide for a virtual laboratory from which to study dynamics of real-world systems, where experimentation is otherwise difficult (Magliocca et al., 2013). In many research projects models act as a platform for integration of findings of different research groups, requiring a