CASE STUDIES OF LOCAL, REGIONAL AND GLOBAL APPLICATIONS OF ENVIRONMENTAL MODELS

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Summary

This paper briefly describes the way in which environmental models are constructed and applied to environmental problems. It gives a detailed description of an integrated model called IMAGE. IMAGE is an integrated model to assess the greenhouse effect at different spatio-temporal scales. The base run of this model is described, and then an attempt to integrate this model with the RAINS model of acidification in Europe and Asia is described. The need for further interaction and constructive dialogue between model builders and decision-makers is then discussed.

1. Introduction

The Earth is approximately 4.6 billion years old and it is only in the last two hundred years that human activities have had a major impact on the ecosystems that make up the biosphere (Turner, 1990). These impacts have been noticed at increasing areal scales. Prior to the Industrial Revolution in Europe circa 1760 human induced environmental problems were generated on a local scale. Even in the nineteenth and early twentieth century there are numerous case studies of local environmental problems. These included polluted water especially in urban industrial areas, local scale soil erosion, landslides and atmospheric pollution in industrial areas of cities.

The increasing incidence of water-borne diseases such as cholera in the rapidly expanding cities of urbanised Britain caused concern amongst the urban inhabitants as recorded in the environmental health reports at local, urban and regional scales. As economic growth and development continued the scale of the environmental impacts increased from local issues to regional, national, international and even global scales.

The purpose of this article is to describe the ways in which environmental modeling efforts have developed to contribute to the amelioration of such complex problems. Obviously, it is impossible to cover every type of modeling approach, and similarly it is impossible to give an exhaustive review of all the different types of models applied to life support system modeling.

The approach adopted here is therefore necessarily selective but gives a review of the state of the art of modeling life support systems at different spatial and temporal scales. In the following section some aspects of environmental modelling are given. This is then followed by an in depth description of an integrated model to assess the greenhouse effect (IMAGE) which can be used to tackle environmental problems at local, regional and global scales. Finally, on the basis of the description of IMAGE the current state of the art of scientific modeling for contributing to environmental management is reviewed and critically assessed.

2. Modeling the Environment

2.1 Environment

The word "environment" is used in many areas of life. Generally, the word environment means the immediate surroundings. Some would like to define the environment as the immediate surroundings that are conductive to life. Hence, the manned space capsules are the environments which are conducive to life for the astronauts, but they live in a very artificial managed environment which is often controlled by other people far from the outside of their module. On the planets of the solar system, excluding Earth, there is currently no evidence of life; hence, the environment simply refers to the physical, abiotic surroundings of a specific planet.

The exception to this statement is our own planet Earth. On Earth the word environment includes the abiotic and biotic aspects of the surface and near surface phenomenon. Biotic elements include micro-organisms, fungi, plant, bird, fish and animal species and includes humans with their rich and diverse cultures. The abiotic surroundings include the rocks and minerals under our feet, soils, the oceans and other watery environments as well as precipitation and solar energy.

Figure 1 gives a simplified view of the environment split into several separate sectors namely the atmospheric system; the lithosphere or solid surface of the Earth's crust; the hydrosphere including oceans and seas, fresh water lakes and rivers as well as underground water. The biosphere refers to the complex web of all life forms interacting with the abiotic environment.

The biosphere includes the Earth's life forms in the hydrosphere; bird and insect life in the atmosphere and the life forms of bacteria; fungi, plants, animals and birds in the various ecosystems of the globe. Superimposed on the biosphere, but an integral part of it, are the different cultural landscapes of humanity. These include urban areas, remotely settled regions as well as agricultural landscapes of different types. Some researchers have argued that the cultural landscapes are also surrounded by a noosphere. This latter term has two meanings. The first is attributed to Teilhard de Chardin who suggested that there was an imaginary zone of ideas, which encircled the globe (Teilhard de Chardin, 1959). The alternative view of the noosphere, as proposed by Russian writers, is that of a rational re-shaping of the biosphere to become the noosphere (Vernadsky, 1926).

It is perhaps fanciful to think of the inter-net as the physical representation of this network of knowledge or noosphere - although the inter-net does contain vast quantities of information we must not confuse information with knowledge or both with wisdom. Nevertheless, these different spheres make up the earth's environment and may be viewed as complimentary ways of understanding the life support systems of the planet (Serafin, 1988). If we penetrate deeper into the Earth's structure then further spheres have been discovered by interpretation of seismic records. These spheres remain as part of the geological environment with its different pressures and temperatures than those found at or near to the surface of the Earth. It will be noted that is a descriptive model of the environment and shows some, but not all, of the interactions that support life.

2.2 Models

A model is a simplified representation of a system so that the structure and functions of the real system can be better understood. No model can represent the totality of the real world in every detail; hence model building must always require some simplification and abstraction from the real world. The art of scientific modeling is to develop a simple model that captures a large and significant part of the behavior of the real system. This act of artistic creation differs from the other creative arts (e.g. painting, drama, sculpting, music, creative writing including poetry and audio-visual media) in that the art of model building requires some knowledge of earlier literature as well as an appreciation of other models addressing similar environmental problems.

The main difference between the art of scientific model building and other expressions of artistic work is that a scientific model must be able to capture some empirical aspect of the real world. This is vital in science as it permits independent means to test our ideas and hypotheses or theories about the way(s) in which we think a specific environmental system functions. Scientific model building is therefore an act of creative imagination (an art) constrained by criticism from other scientists as well as by the acid test of exposing the predictions of the model to the possibility of refutation by recourse to empirical observations and experiments (Lakatos and Musgrave, 1970).

Scientists develop models to explain some phenomenon in which they are interested. There are many texts on scientific explanation but, for the purpose of this article, one route to scientific explanation and the role of models in this approach will be described. We begin with some perceptual experience concerning our world or system of interest. Through the perceptual filters of our mind, our imagination and language a scientist is able to create an apriori model of how he or she thinks the system of interest functions. Any model should contain one (or more) hypothesis within its structure.

An hypothesis is a speculation about the way in which the system functions. It could be suggested that a good scientist should reject an hypothesis each day before breakfast to keep the mind fertile and active. Once one or more hypotheses are stated using a natural language, mathematics, equations or computer code then some experimental designs can be developed to define, classify and measure aspects of the system of interest so that relevant data is collected. Once the relevant data is collected as a data set then the model is subjected to one or more sets of verification procedures.

The verification procedures can include several statistical methods to amass evidence to indicate that the hypothesis has some support or not. It should be pointed out that some philosophers of science see the testing of hypotheses not as a process to confirm the hypothesis but as a way of attempting to reject the hypothesis and the model upon which it is constructed. Popper in particular sees the advance of science as a series of bold conjectures (hypotheses) exposed to the hazard of refutation (testing to reject the hypotheses) (Popper, 1959; Popper, 1969).

Other philosophers of science, however, suggest that if each and every hypothesis was tested to reject it then science would rarely progress (Kuhn, 1970). For present purposes we need not dwell too long on these fundamental differences in the role of testing in science. We can, however, agree with Harvey when he noted that, "All we can do is to establish a certain degree of confidence in the theory. Statements contained in a theory, which commands considerable support we may call scientific laws. The difference between a hypothesis and a scientific law may be regarded, thus, as a matter of degree of confirmation or degree of confidence" (Harvey, 1969, 35).

2.3 Scale

The choice of scaling units is important in modeling. Often models can be termed static or dynamic. Static models address problems conceptualised at one point in time. Examples of such models would be a linear programming model, or an input-output or an econometric model. In some cases, these models can be made dynamic. A dynamic model explicitly incorporates time into the modeling framework. Some models, for example, consider changes over several minutes or hours whilst other models may examine changes to the environment over millions or even billions of years.

The scale of spatial resolution is also important. Often the early models of the environment developed in the 1960s and 1970s were aspatial, i.e. no geographical dimensions were explicitly incorporated into their structure. With the development of more powerful computers and software packages it has become possible to include spatial disaggregation into modeling efforts. The development of Geographical Information Systems (GIS) based essentially on relational databases with an explicit geographical set of co-ordinates has been a major development in modeling spatial aspects of the "real world". Today, many models do include spatial dissaggregated data and can display the information at local, regional, national, international and global levels of resolution.

The problem of scale is important for both substantive and technical reasons. At the substantive level the spatial and temporal scales chosen by the model builder depend on the problem he wishes to investigate as well as on the quality and quantity of available data for the study. From a technical perspective there are four major aspects that need to be considered. First, if there are many spatial zones and if these are to be modelled over a long temporal horizon then many calculations would be needed. In some cases more powerful computing facilities are required to ensure that the calculations for the spatio-temporal scales can be embraced. The current Atmospheric General Circulation models (AGCMs), for example, have increased their temporal and spatial scales - but have required the use of supercomputers to simulate climatic change across the globe. Second, any dynamic mathematical model, which is to be used as a computer simulation model needs to incorporate a solution time interval (dt).

The choice of this solution time is not altogether arbitrary. If dt is set at 0.1, for example, then the computer has to calculate the equations ten times to represent one time unit in the model. If dt is set at 0.001 then the same model has to make 1000 calculations to solve the equations for the same one time period. Obviously, decreasing the solution time (dt) increases the length of time the model has to run on a computer and this can increase the cost of the simulation. There are, however, more important technical aspects than mere cost, namely the problems of errors and the solution of stiff equations.

Third, running computer simulation models can include the propagation of errors. Since each iteration is made to solve the equation for a given solution time rounding errors can increase. These errors are due to the fact that any computer will solve equations to a given degree of accuracy, say, 16 decimal places.

If, however, the equations need to be solved 1000 times per time period then rounding errors can build up in the solution of the equation. It is also possible that the method of integration to solve the equations also contain errors of approximation. If, for example, the Eulerian method of integration is used then some inaccuracies can be introduced. Other methods of integration such as the Runge Kutta third approximation method can also be used but these methods can also introduce inaccuracies.

Fourth, when a model is built some elements in the system may move very quickly, for example wind flow, whilst others will take longer to change such as seasons. Hence, many environmental models contain both fast and slow dynamics within their structure. Such dynamics are called stiff equations and are difficult to resolve. These stiff equations are present in many models of life support systems ranging from biogeochemical flows at cellular and large spatial scales as well as in many complex ecological-economic models of sustainable development. In the art of model building eternal vigilance is required if we are not to be misled by technical aberrations.

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Bibliography

Alcamo J, Amann M, Hettelingh J-P, Holmberg M, Hordijk L, Kamari, J Kauppi L, Kauppi P, Kornai, G and Makela A. (1987). Acidifciation in Europe: A Simulation Model for Evaluating Control Strategies. *Ambio* **16**, 232-245. [Application of an acidification model for pollution control across Europe.]

Alcamo J. (1994). *IMAGE2.0 Integrated Modelling of Global Environmental Change*. Kluwer Academic Press, Dordrecht. [Update of IMAGE1.]

Alcamo J, Leekmans R and Kreileman E (Eds.) (1998). *Global Change Scenarios of the 21st Century Results from the IMAGE2.1 Model,* Oxford: Pergamon, xii + 296 pp. [A major reference to recent work with IMAGE2.1.]

Arrhenius S. (1896). On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground. *Philosophical Magazine*, **41**, 237-76. [An early paper predicting global warming due to CO2 in the atmosphere.]

Harvey D. (1969). *Explanation in Geography*. London: Arnold. [A good exposition of explanation.]

Houghton RA., Hobbie J. E., Melillo JM., Morre B., Peterson BJ., Shaver GR. and Woodwell GM. (1983). Changes in the Carbon Content of Terrestrial Biota and Soils between 1860 and 1980: A Net Release of CO2 and the Atmosphere. *Ecological Monographs* **53**, 3, 235-262. [A detailed account of CO2 releases for the land to the atmosphere.]

Houghton J. (1998). *Global Warming: the complete briefing*. Cambridge: Cambridge University Press. [An update on the IPCC scientific view of global warming.]

Huggett R. J. (1993). *Modelling the Human Impact on Nature*. Oxford: Oxford University Press. [A basic introduction to modeling.]

Kuhn T. S. (1970). *The Structure of Scientific Revolutions.* Chicago: Chicago University Press. [Argues that revolutions occur in science.]

Lakatos I. and Musgrave A. (Eds.) (1970). *Criticism and the Growth of Knowledge* Cambridge: Cambridge University Press. [A debate between Popper and Kuhn on the growth of scientific knowledge.]

Moffatt I. (1992). *The Greenhouse Effect Science and Policy in the Northern Territory Australia*. Canberra: Australian National University. [Linking simulation of several AGCM's to policy making in North Australia.]

Popper K. A. (1959). *Conjecture and Refutations: The Growth of Scientific Knowledge.* London: Routledge and Paul Kegan. [A description of the growth of scientific knowledge.]

Popper K. A. (1969). *The Logic of Scientific Discovery*. London: Hutchinson. [An examination of the logic of scientific discoveries.]

Posch M., Hettelingh JP. Alcamo J. and Krol M. (1996). Integrated scenarios of acidification and climate change in Asia and Europe *Global Environmental Change* **6**,4, 375-394. [Linking RAINS and IMAGE models to explore acidification in Asia and Europe.]

Rotmans J. (1990). *IMAGE: An integrated Model to assess the Greenhouse Effect*. Dordrecht: Kluwer Academic.[A description of the original IMAGE model.]

Serafin R. (1988). Noosphere, Gaia and the science of the Biosphere *Environmental Ethics*, **10**,2, 121-137.[A review of some ideas of global biosphere and noosphere.]

Teilhard de Chardin P. (1959). *The Phenomenon of Man*. London: Collins. [Religious view of humanity and the idea of the noosphere.]

Turner B. L. (Ed.) (1990). *The Earth as Transformed by Human Activity.* Cambridge: Cambridge University Press. [Detailed study of human activities and their impact on the rest of the planet.]

Vernadsky V. I. (1926). *Biosfera Lenningrad*, Nauchekhizdat. [Classic study of the biosphere and noosphere.]

Biographical Sketch

Dr. Ian Moffatt is a Senior Lecturer in the Department of Environmental Science at the University of Stirling, Scotland. He has BSc (London University) in geography and geology; a MSc in urban geography and a PhD in urban system modelling from the University of Newcastle Upon Tyne, England. He has been a lecturer at the University of Liverpool, England, a Senior Research Fellow at the Australian National University and a founder member of the Department of Environmental Science at the University of Stirling, Scotland. He has lectured extensively in Europe, North America, China and Australia. He has been involved in policy making into improving water quality in estuaries using regulative and economic incentive approaches as well as being a scientific adviser to the Northern Territory Governments Advisory Committee on the Greenhouse Effect (1990-1993). His main research interests are into sustainable development from an interdisciplinary perspective at different spatial and temporal scales. This research includes the development of dynamic simulation models for understanding and contributing to the management of environmental systems. He has published numerous scientific papers and six books; the last two are contributing to making development sustainable.