System Dynamics and Earth system science: Bridging the gaps between research and education

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Introduction

In the past six to seven years, a growing consensus has emerged over the powerful role that system dynamics can play in education reform. This consensus has been fueled by educators who have successfully utilized dynamic modeling in their classrooms (Draper and Swanson, 1990; Hopkins, 1992; Roberts, 1978), practitioners of systems modeling and thinking in various professions (Forrester, 1993), and educational researchers and standards/review bodies (AAAS, 1989; Betts, 1992). These groups hold in common the view that principles of system dynamics - and the computational tools used to illustrate them - can provide a relevant foundation of core concepts and skills to integrate classroom studies, both across subject areas and through time.

In the following paper this author discusses another role that dynamic modeling can play in enhancing education at all levels, by integrating classroom studies more closely with the 'real' data and insights of the scientific research enterprise (in particular, the Earth system or 'sustainability' scientific community). Current practice at the precollege level focuses mainly on using 'idealized' models as heuristic teaching tools to illustrate basic concepts in science, math and system dynamics. By using 'real' models and data of Earth system scientists, learning goals fostered through the 'classic' approach are preserved, but can be extended in unique ways. In the paper I illustrate this point by discussing the Biosphere 2 Center's experiences in developing precollege Earth system science curricula utilizing system models in the Stella environment. Challenges implied in the approaches I suggest are discussed, as are opportunities.

Earth system science and science education: A widening gap

The pace at which scientific knowledge relevant to issues of the global environment is generated has increased tremendously in recent years. Connected to the global emergence of 'sustainability' as a salient issue over the past twenty five years (and its rising profile in international policy deliberation over the past ten years), this knowledge-generation is reflected in large-scale data generating and modeling projects (such as NASA's Mission to Planet Earth), international efforts aimed at informing global environmental policy formulation (such as the Intergovernment Panel on Climate Change) and a myriad of university-based research projects addressing the social, scientific, economic, and political dimensions of sustainability (e.g., Clark, 1989; Haas, Keohane, and Levy, 1993; Costanza, 1991). Together, this research is now often grouped under the term Earth system science, a multidisciplinary body of theory, large datasets, and sophisticated models that illuminates how the Earth works.

This trend of increasingly fast-paced innovation and discovery is reflected across many other scientific fields as well, most notably in the biological and medical sciences. It is becoming increasingly clear, however, that the capacity of science to extend our understanding of the world has outstripped the capacity of educational institutions, resources, and curricula (particularly at the precollege level) to adapt to and innovate around these insights. An unfortunate result of this phenomenon is that educational content and methodology become increasingly irrelevant, as they cannot keep pace with a constantly evolving base of knowledge and data. Because of this, the 'canned' content - with even the most recent textbooks becoming outdated over the course of a school year - and passive pedagogy of traditional education methods leave students disconnected from both the inquisitive methods and evolving products of the research enterprise.

Sorcerer's tools in the hands of children: Dynamic modeling in the precollege classroom

With the advent of computer-based tools such as High Performance Systems' Stella II, computer models of complex systems are now accessible to students at all levels of education. Accordingly, concepts and phenomena relevant to Earth system science issues that were once less accessible (or inaccessible entirely) to precollege students are able to be illustrated and analyzed through construction of and interaction with models of complex systems.

Most educators have, to this point, used dynamic models to illustrate fundamental concepts in science (such as, in the environmental sciences, the dynamics of predator-prey relationships and the structure of food webs), mathematics and system dynamics (Prince, 1992; Halbower, 1991), and to provide a framework for exploring discipline bridging problems and issues (Lofdahl, 1992). For the most part, however, models utilized in precollege systems-based curricula are not the same models that are used by scientists in their work, and do not often draw on 'real,' published scientific datasets. However, there are exceptions to this (e.g., ESSCC, 1995-6; Simons, 1992), and this observation should not be taken as a critique of current practice, as educators have different learning goals in using models.

Rather, this author wishes to outline another approach to using dynamic models in education, particularly in Earth system science education. This approach involves use of the datasets and 'real' models of professional scientists to investigate the same pressing questions that they use those models to elucidate. The approach is designed to increase the relevance of classroom studies and provide a framework for bringing students closer to the frontiers of human knowledge, in addition to illuminating multidisciplinary topics in Earth system science and general principles of system dynamics. The approach is outlined by discussion of the Biosphere 2 Center's use of dynamic models in a variety of curricular settings.

In 1995 the Center identified a recently published model of carbon cycling within terrestrial ecosystems (Melillo et al, 1993) - used in a variety of global change studies and integrated assessment models - and programmed the model (in slightly simplified form) into a multi-tiered learning environment within Stella II (see Figures 1-3). The Terrestrial Ecosystem Model (TEM) can be parameterized to simulate the movement of carbon through any terrestrial ecosystem, and has been used by its authors to estimate global net primary production (NPP), as well as potential future NPP under rising atmospheric CO2 and changing climate. Utilizing geo-referenced temperature data and atmospheric CO2 data available via Internet, the TEM can be run for any ecosystem in the world under current environmental conditions, and under the output data of

NASA General Circulation Models (Russell et al, in press). Students can thus use the TEM to address the same questions, using the same model and data, as the scientists who developed the original TEM.

Because of the 'layered' structure of the Stella learning environment, students at many levels of education can use the TEM in grade-appropriate curricular contexts. This structure enables students to interact with the system, its properties, and underlying assumptions at different levels of complexity. Middle school students, for example, might primarily interact with the high-level mapping layer of the TEM environment (Figure 1); they can explore how small changes in certain parameters affect the whole system, and use the model to help learn basic concepts about environmental change. High school students, such as those in Marana, AZ. who are piloting the Biosphere 2 'Global Change Testbed' curriculum (Tosteson and Marino, 1996), interact with the model at the modeling layer (Figure 2), exploring interrelationships between system components and using the model as an environmental policy analysis tool. Undergraduate students in the Biosphere 2 Center 'Earth Semester' program will delve deeper into the scientific assumptions and data that underlie the model's structure, building the model from scratch and making changes - if justified by relevant scientific work - to those assumptions. A student might, for example, question whether the TEM realistically simulates the effects of CO_2 on photosynthesis. (S)he might conduct her own research of the scientific literature and investigate a hypothesis of what a different functional relationship would imply for the ecosystem's photosynthetic capacity under high CO_2.

The TEM model not only integrates topics from different subject areas (i.e., photosynthesis and energy use), but it can effectively integrate studies across grade levels. The model's relevance across the precollege and undergraduate curriculum is directly tied to its 'realness' and scientific rigor: As students 'tunnel' through the model's layers, they are in fact digging down to scientific assumptions and data that represent the edges of human understanding. As they do this, they are also learning about system dynamics, terrestrial ecosystems, 'real' data, and global change science and policy, all by asking the same questions and using the same tools employed by professional scientists.

'Real' models and Earth system science education: Challenges and opportunities

The example briefly reviewed above represents a variation on the common use of dynamic models in the precollege science classroom. It is not argued that use of 'real' models should replace the effective, demonstrated practice of using more generic models as teaching tools. Rather, it is suggested that this approach may offer unique learning opportunities that expand the relevance of dynamic modeling to issues pertaining to the global environment (and, potentially, to other scientific fields). When scientifically rigorous models are used, the traditional learning outcomes of a 'systems' education are preserved but extended: At younger grade levels, the excitement of working with authentic scientific tools to address real-world questions about the global environment can add motivation and compelling relevance to a curriculum. And older students with greater knowledge are empowered to push the model - and their own knowledge - closer toward the edges of human understanding.

Early results from our work are promising. Students at Marana HS commented that use of 'real' scientific tools made their classroom studies more engaging. Not only were the students at Marana able to use the TEM effectively to address policy-relevant questions about future climate change, but they consistently commented that their learning would be greatly enhanced by actually building the model from 'scratch.' These comments are leading us to explore a deeper meshing of 'real' dynamic modeling with constructivist pedagogical principles.

This approach is, of course, not a 'panacea' by any means; nor is it without its difficulties. The challenges of model building and curriculum development are magnified when attempting to make very complex scientific models accessible to students. Close interactions are required along a non-traditional continuum of professional fields, from scientists to science-literate model developers, educators, and evaluators. Yet, the mandate for such interactions appears to be clear enough: The prospect of students spending their time learning dated, irrelevant material in this exciting time of discovery and innovation should be as alarming to scientists and educators as it is unappealing to students.

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