Student understanding of complex Earth systems

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ABSTRACT

Most environmental issues involve near-surface earth systems that often exhibit complex spatial characteristics and dynamics. Conceptual understanding of complex earth systems influences the development of effective policy and management strategies. Students, like all people, organize knowledge and reason about environmental issues through manipulation of mental models. A mental model is a relatively enduring and accessible, but limited cognitive representation of an external natural phenomenon. The nature of near-surface earth systems may present major cognitive difficulties to students in their development of authentic, accurate mental models of earth systems. These cognitive difficulties include conceptualization of natural earth environments as systems, understanding the complex characteristics of these systems, and the application of conceptual models of complex earth systems to support environmental problem solving. This paper reviews the nature of near-surface earth systems that exhibit complex behavior and the cognitive and epistemological issues that students may experience in understanding these systems. Finally, I suggest that the same learning issues that students face in the classroom also are encountered by

experts, policy managers, and stakeholders while they develop solutions to environmental problems. Therefore, educational research of student learning in earth science may not only support the development of improved pedagogical practices and learning environments, but this research may also support improved environmental decision making.

INTRODUCTION

Understanding near-surface earth systems is central to the development of solutions to important environmental issues arising from the growth of human populations and economic activities (Lubchenco, 1998). A recent report from the National Research Council (2000), *Grand Challenges in Environmental Sciences,* outlined eight major challenges facing human society: biogeochemical cycles, biological diversity and ecosystem functioning, climate variability, hydrologic forecasting, infectious disease and the environment, institutions and resource use, land-use dynamics, and reinventing the use of materials. The NRC report also highlighted the need for new models of science education and training that focuses on developing expertise in problem-orientated science (Stokes, 1997). In particular, the need for expertise that can address interdisciplinary problems through the efforts of collaborative groups that integrate the natural sciences, social sciences and engineering around common research problems was cited by the report. Restoration of the Florida Everglades, for example, involves the close collaboration of teams of experts including civil engineers, hydrogeologists, restoration ecologists and economists.

Most environmental issues involve complex earth systems, which are defined as near-surface earth systems that exhibit complex spatial characteristics and dynamics. There are three fundamental challenges in understanding complex earth systems. The first challenge is the **conceptualization of natural earth environments as systems** with accurate definition of boundaries and the nature of interactions between the elements of the system. Descriptions of the processes that transfer and manipulate matter and energy within the systems and across system boundaries as well as relations between one system and other systems should also be included in an accurate conceptualization. The second challenge is the characterization and explanation of the **complex nature of earth systems** through a description of the system's state over space and time, self-organization, or emergence of structure or patterns. A system's state encompasses a description of the all the important variables of the system and how they change under both steady state and non-equilibrium conditions. The third major challenge is the **application of conceptual and scientific models of earth systems** to support problem solving and the development of effective environmental policy (Oreskes, 1994).

Experts, policy managers, and stakeholders have been found to commit cognitive errors when reasoning about environmental issues. The behavior and dynamics of earth systems are often complex enough to make prediction of future behavior difficult (Doyle, 1998). Differences in the conceptualizations of systems by stakeholders has contributed to conflict concerning ecosystem (Hurley, 2003) and water resources management (Sneddon, 2003), through differences in assumed cause and effect mechanisms and average characteristics of the systems. People's conceptualizations of earth systems, when applied to risk perception, are also often ill-structured leading to incorrect perceptions of risk due to global warming (Kempton, 1991), radon (Bostrom, 1993), and electric fields (Morgan, 1990).

Environmental decision-making can present policy managers and stakeholders with serious behavioral, cognitive or technical demands (Schofield, 2004). As a result, innovative decision making processes have directly incorporated learning and adaptive management within the processes to identify and minimize cognitive errors (Alen, 2001, McDaniels, 1999, Schofield, 2004). Adaptive management techniques utilize cycles of implementation, evaluation, and improvement to develop more effective environmental management strategies. I propose that a better understanding of the cognitive and epistemological issues students have in understanding and reasoning about complex earth systems, along with teaching methods that directly address these learning issues, are needed to support reform in both earth science education and the management of major environmental issues facing human society.

THE NATURE OF COMPLEX EARTH SYSTEMS

Systems that exhibit complex behavior, often labeled 'complex systems', consist of a large number of mutually interacting and interwoven parts, entities or agents. They are woven out of many parts, the Latin *complexus* comes from the Greek *pleko* or *plektos*, meaning "to plait or twine". The concept that systems can exhibit complex behavior spans almost every scientific, engineering, and social science discipline. Systems in physics (Bak, 1987, Bar-Yam, 1997), chemistry (Prigogine, 1978, Whitesides, 1999), biology (Kitano, 2002), ecology (Scheffer, 2001), earth sciences (Phillips, 1999), and engineering (Fisk, 2004, Tomlin, 2005) all have been found to exhibit complex behavior.

Systems are defined by the nature of their boundaries, the types of interactions between system elements and the structure of the system. Complex systems are open systems due to the constant import and export of energy across system boundaries (Goldenfeld, 1999, Katchalsky, 1967, Nicolis, 1977). Complex systems also typically exhibit nonlinear relationships between system elements, with both negative and positive feedbacks. Finally, complex systems are also commonly structured in a hierarchy, where the components of the system are themselves complex adaptive systems or scale-independent networks (Strogatz, 2001). These features have both deterministic and stochastic components that are essential to system stability.

Though complex systems are usually far from equilibrium, they often exhibit the appearance of stability through the generation of spatiotemporal patterns through self-organization, and bifurcations to new stable states (Bak, 1996, Bak, 1987, Bar-Yam, 1997, Barabási, 1999, Carlson, 1990), such as the cloud structure in a hurricane or tornado. Self-organization refers to a process in which the internal organization of a system, normally an open system, increases automatically without being guided or managed by an outside source. Self-organizing systems typically (though not always) display emergent properties. What distinguishes a complex system from a merely complicated system? In a complex system, some behaviors emerge as a result of the patterns of relationship or interactions between the elements or components of the system, not through some external agent that imposes order.

Other complex systems can exhibit chaotic dynamics, where the state of the system is sensitive to initial conditions. This type of complex system is typical of highly turbulent flow in fluids, among others (Eckmann, 1985, Goldenfeld, 1999). In some cases, nature can produce complex structures in simple systems, while other systems obey simple laws in complex situations, therefore nature is both complex and chaotic (Goldenfeld, 1999). Chaotic systems often exhibit exponential or other distributions (Gheorghiu, 2004), where improbable event are orders of magnitude more likely than events that follow the Gaussian distribution. Estimates and predictions of system future behavior, particularly Gaussian estimates, formed by observations collected over short time periods provide an incorrect picture of large-scale fluctuations.

Exceptional events in complex systems are often not that rare (Goldenfeld, 1999). These observations have interesting implications for the traditional uniformitarism versus catastrophism debate in the geosciences.

Since each complex system is different, fundamental laws describing non-equilibrium, complex systems are likely to remain elusive. Instead, heuristics developed through study of one complex system can be applied to develop understanding of other systems (Goldenfeld, 1999), mirroring the role of analogy in classic geologic inquiry. Fundamental laws describing complex systems may not be possible because of difficulties in upscaling, which Anderson (1972) defines as the constructivist hypothesis (Anderson, 1972, Goldenfeld, 1999). The constructivist hypothesis fails when confronted with the twin difficulties of scale and complexity. At each level of complexity, entirely new properties can arise in complex systems, requiring the development of insight and understanding through research of fundamental questions appropriate to that scale. These authors, on the other hand, suggest that common analysis techniques and methods may result in knowledge about certain types of complex systems that can be transferable to other situations, an example of analogous reasoning.

The earth system perspective developed in the 1980's in response to the growing understanding that large-scale environmental change required an integrated view of the mutual interactions between the biosphere, human society and the earth. Earth system science focuses on the key processes that link the physical, chemical, biological and human dimensions of the earth system, employing relevant problem solving methods and system modeling concepts. Earth systems are defined based upon the transfer of matter and energy across real or imaginary boundaries that separate the system from the rest of the universe, and the cycle and storage of matter and energy within the system. Characterization of earth systems is typically focused on the nature of the boundaries and structure of the system, feedbacks and other connections within and between systems, and the dynamics of systems variables that define the phase space of a system. For instance, the watershed or drainage basin has become the default system conceptualization to examine many questions concerning pollutants and water quality and water resources. Figure 1 shows maps of the Guadalupe and San Antonio River watersheds, the systems of interest for the proposed Texas Hydrologic Observatory. Complex earth systems typically operate across a wide range of time and spatial scales. Complex spatial structures, such as those found in fluvial sediments along the Mississippi River (Fig. 2) or phytoplankton blooms off of the coast of Japan (Fig. 3), can control the movement of matter and energy through the systems, controlling the overall state of the

systems. Complex system dynamics have been observed in species interaction in ecological systems (Brown, 2001), catastrophic shifts in ecosystems (Scheffer, 1991, Scheffer, 1993, Scheffer, 2001), stability of food webs (Neutel, 2002), and geologic systems (Aki, 1995, Culling, 1988, Meijer, 1990, Phillips, 1992, Phillips, 1999, Ravelo, 2004, Thomas, 2001, Triantafyllou, 1995, Turcotte, 1995, Valentine, 2002).

Current scientific inquiry seeking to address pressing environmental issues involving global, regional and local earth or environmental systems is focused on building mechanistic understanding of the complex system and the impact of anthropogenic and geogenic perturbations have on the stability and functioning

of earth systems. Examples include the restoration of natural ecosystems such as the Everglades, the dynamics of water cycling as a function of hydrology, or the impact of nitrogen loading from fertilizer on phytoplankton population dynamics in lakes and estuaries. It is typical that there is a large amount of uncertainty concerning system characteristics making difficult the accurate prediction of complex earth systems and the development of effective environmental policy.

Three major inquiry methods have been adopted to address these challenges: simulations, characterization of the properties and dynamics of natural systems over a range of spatial and temporal scales, and experiments on model systems where conditions can be controlled and causal relationships established (Scheffer, 2001). The results of these different types of inquiry must be carefully synthesized because each is limited in important ways. Simulations can only represent a small amount of the complexity of natural systems due to incomplete knowledge of initial conditions and phase space over

time and space, though the development of new modeling techniques coupled with increased computing power have dramatically increased our ability to simulate complex systems. Recent developments in modeling techniques include the application of Bayesian statistics (Brooks, 2004), fractal analysis (Neuman, 2003, Strogatz, 1994, Turcotte, 1994, Turcotte, 1995), cellular automata, neural networks or other hierarchical techniques (Guermond, 2004, Mitchell, 1996, Peak, 2004, Wu, 2002), or fractional calculus (Benson, 2001, Clarke, 2005, Schumer, 2003).

Direct observation of the characteristics and dynamics of natural earth systems is possible due to the development of new sensor technologies, including remote sensing (Donoghue, 2002, Power, 2005, Schmidt, 2005) or chemical sensors that can directly characterize water chemistry (Bakker, 2004, Vo- Dinh, 2000, Wolfbeis, 2004). At other scales, particularly characterizing earth systems over geologic time scales, earth scientists use data proxies to characterize other variables of interest, such as O16/O18 ratios found in Artic/Antarctic ice cores as a means to study temperature conditions and changes in

paleoclimates.

Scientists have only limited control of conditions in natural experiments making establishment of casual relationships difficult. Laboratory experiments are frequently employed for purposes of evaluating the validity and reliability of the data proxies or understand system mechanisms (Daehler, 1996, Drake, 1996, Ives, 1996), especially where casual relationships between limited number of variables need to be established. Laboratory-scale experiments, however, can lack the complexity of real systems thereby limiting the usefulness of this reductionist approach (Carpenter, 1996).

Scientific exploration of the nature and dynamics of complex earth systems is relatively new and evolving where a challenge lies in creating inquiry that adapts traditional modes of geologic inquiry to new questions and techniques (Baker, 2000, Frodeman, 2000, Frodeman, 2003, Sarewitz, 2000, Schrader-Frechette, 2000).

SUPPORTING CONCEPTUAL CHANGE THROUGH MODEL-BASED LEARNING AND AUTHENTIC INQUIRY

Supporting student development of meaningful conceptual understandings of science and its ways of describing, explaining, predicting and controlling natural phenomena remains one of the core goals of science education. In order to meet this important goal, we need to understand the major learning difficulties that a particular knowledge domain present to students. We are just beginning to be able to articulate the specific cognitive, epistemological, and learning difficulties students have in understanding complex earth systems. While some of these characteristics are shared by other, more traditional scientific disciplines, taken together they form a set of characteristics that likely affect learning about complex systems. There are three

cognitive difficulties people likely have in reasoning about complex systems. The first issue is that many earth processes occur at spatial and temporal scales beyond human experience (Dodick, 2003, Giorgi, 1997). The second issue entails the difficulty people have in developing accurate conceptual models of complex systems when there are a number of variables controlling system behavior, especially when the interactions between variables are nonlinear (Berger, 1998). It is likely that in most cases student's assumptions about causality default to simple, linear, casual relationships between a small number of variables (Grotzer, 1993). The final cognitive issue involves the tendency to focus on average properties of a system, often discarding data far from the
average as noise (Petrosino, 2002). In most systems far from equilibrium, average properties are rarely relevant because it is the extreme events or characteristics that dominate the nature of the system (Goldenfeld, 1999).

Epistemologically, there are major issues concerning the nature of inquiry methods and evidence that can be used to describe explanations concerning complex systems, a characteristic that has important implications for environmental policy (Palumbi, 2005). Applying standards of scientific inquiry that are used to assess the link between evidence and explanation common in reductionist studies may be too restrictive given the nature and our current understanding of complex systems. Because of the difficulties in both the study and modeling of complex systems, it is likely that relaxed standards of scientific evidence and inquiry are going to have to be adopted when science is needed to inform policy instead of adopting a policy of inaction. The final issue concerns the social nature of complex earth systems and environmental issues. Most environmental issues are value-laden and strongly socially constructed. Secondly, the study of complex earth systems and environmental issues require an interdisciplinary approach (Brewer, 1999, Hansson, 1999, Karlqvist, 1999, Wijkman, 1999), an approach that is counter to the more common specialization of knowledge.

This brings us to consider appropriate educational strategies that best develop student conceptual understanding about the nature of complex earth systems. The specific cognitive and epistemological issues described above can be incorporated into the larger learning challenges discussed in the introduction, namely student conceptualization of earth systems, understanding the complex behavior of these systems and applying this knowledge toward the development of environmental policy. Conceptual change related to these three challenges is directly related to student development of, manipulation of,

and reasoning with internal or mental models (Clement, 1989, Clement, 2000, Gobert, 2000). A mental model (Doyle, 1998) is defined as a relatively enduring and accessible, but limited cognitive representation of an external natural phenomenon (Table 1). The structure of a mental model maintains the perceived structure of the external system (Johnson-Laird, 1983). The theory of mental models has been extended to explain deductive reasoning (Johnson-Laird. P.N., 1993) and learning (Bransford, 1999). Mental models can be expressed through words, drawings, objects or other symbols, allowing

social comment and criticism. Those expressed models adopted by groups are defined as conceptual models (Greca and Moreira, 2000; Libarkin et al., 2003). Scientific models, then are a special type of conceptual model, adopted and used by scientists as cognitive tools to aid in experimental design, develop understanding of complex systems through comparisons with observations, or to make qualitative and quantitative predictions concerning system behaviors under specified conditions.

Though the research is limited, it is likely that many students have difficulty in understanding earth systems of even modest complexity, predicting future system behavior in a variety of scenarios, and reasoning correctly about complex environmental issues because of misconceptions, inaccuracies or incompleteness in their mental models of these systems (Ekborg, 2003, Forrester, 1994). Instructional sequences and learning environments that stress model-based teaching and learning may address student development of more accurate mental models of complex earth systems (Boulter, 2000).

Modeling as a pedagogical tool involves cycles of model construction, characterization, application to specific problems, evaluation and revision. Modeling emphasizes forms of knowledge representation and topics including visualization, data structures, and measurement and uncertainty (Table 2). Model-based learning also supports student understanding about the nature of science because model-based learning typically stresses the relationship between mental models and scientific models. Scientific models are major outcomes and products of scientific inquiry, and understanding the nature of science requires an understanding of these models within a philosophical, scientific and historical context (Gilbert, 2000), (Grandy, 2003).

Student manipulation of mental, conceptual or scientific models is only one aspect of effective instructional sequences. Educational research has shown that learning by authentic inquiry is the most appropriate method of instruction to instill scientific understanding and reasoning in students, such that the instructional technique has become embedded in almost all national and state science standards (National Research Council, 2000). Authentic (i.e. scientific) inquiry is defined by educators as the activities that scientists engage in while conducting research (Dunbar, 1995, Latour & Woolgar, 1986).

Because scientific inquiry is a complex process that varies across disciplines in term of required cognitive & metacognitive processes, epistemology, and methods, there is significant debate in the science education literature about the nature of authentic inquiry and how it should be implemented in different educational settings (Chinn, 2002, Minstrell, 2000). Recent analyses show that authentic inquiry has not been incorporated into most classroom activities in secondary schools and universities (Chinn & Malhotra, 2002). A host of reasons have been cited to explain why authentic inquiry is uncommon in classrooms including the characteristics of the students and/or teachers, and the constraints of the learning environment.

Inquiry-based learning is a student-centered, active learning approach focusing on engaging students in questioning, critical thinking, and problem-solving. For instance, the Legacy Learning Cycle, developed at the Learning Technology Center at Vanderbilt University conceptualizes authentic inquiry as cycles of challenge, thoughts, perspectives and resources, assessment, and wrap-up (http://iris.peabody.vanderbilt.edu/slm.html). In most cases, student manipulation of models is not conceptualized as a major component in inquiry-based learning. Authentic inquiry could be reconceptualized to place manipulation of conceptual models as its core activity, an idea supported by the

analysis of potential learning issues connected with student understanding of complex earth systems presented above and the importance of modeling in scientific research (Fig. 4).

Students show evidence of being able to reason scientifically and engage in scientific inquiry (American Association for the Advancement of Science Project 2061, 1989) when learning is focused on challenging scientific problems with personal significance, efforts are scaffolded, and evidenced-based reasoning is developed from personal observation and experiences. The role of authentic inquiry in developing student's "scientific habit of mind" (Duschl, 1997) assumes students can learn the cognitive and manipulative methods of science exploration that generate data and evidence. It also assumes that students can use the reasoning and argumentation skills needed for model development and evaluation that link evidence to explanations. A scientific habit of mind is an example of a cognitive strand, which we define as a set of interdependent cognitive and metacognitive skills and strategies (e.g. developing mental models, connecting multiple representations, visualization, using iterative processes, and critical thinking), that allow students to engage in scientific inquiry. Jim Minstrell has used a strand analogy to describe the nature of preconceptions in physics students and the role of effective instruction in developing understanding (Minstrell, 1989):

> *Students initial ideas about mechanics are like strands of yarn, some unconnected, some loosely interwoven. The act of instruction can be viewed as helping the students unravel individual strands of belief, label them, and then weave them into a fabric of more complete understanding. Rather than denying the relevancy of a belief, teachers might do better by helping students differentiate their ideas from and integrate them into conceptual beliefs like those of scientists.*

Serious questions remain on how best to implement instructional sequences that embed model-based reasoning about complex earth systems within inquiry-based learning. Information technology remains one of most promising strategies to meet these educational goals. The use of information technology to support student understanding of complex earth systems through authentic inquiry learning should employ learner manipulation of complex data sets and physical models, the development and testing of conceptual models based on available evidence, exposure to authentic, complex and ill-constrained problems, and contain explicit instruction in cognitive and metacognitive strategies. Because of these characteristics, the design and development of Information technology-based learning environments is directly supported by research activities conducted by university, government and industry and helps integrate research and education.

There is a need to enhance earth & environmental science instruction at all levels through the further development and incorporation of effective and innovative information technology-based learning materials in ways that build on the strengths of the Internet and distributed networks, and the availability of large environmental data sets. Given the individuality of instructional style and curricula, the development of information technology-based instructional materials should be highly modular in nature
to foster dissemination, where each module emphasizes the development of specific cognitive strands (e.g. connecting multiple representations, visualization, using iterative processes, critical thinking) and competencies in learners. In addition, further efforts need to be placed on assessment of design and implementation strategies using authentic assessment methodologies.

SUPPORTING REFORM OF EARTH SCIENCE EDUCATION

In the discourse above, I outline major learning challenges, cognitive errors, and epistemological issues surrounding student learning about complex earth systems. I also describe potentially effective instructional strategies, namely model-based learning, authentic inquiry and the role of information technology to support learning within classroom contexts, which may address these learning challenges. The question remains about the relationship between these rather specific conclusions and larger issues of tertiary science education reform. Several major issues have guided reform efforts in the United States, including the poor retention of scientific knowledge and lack of cognitive skill development in students, the low retention of students in science, especially those from underrepresented minorities, and the limited scientific literacy among the American public.

In a series of reports, national committees have focused on the state of science education in higher education institutions (George, 1996, Ireton, 1997, Resnick, 1987, Stout, 1994, The Boyer Commission on Educating Undergraduates in the Research University, 1998). Calls for reform of science education, including earth and environmental science, at the university and college level are not new. Passivity in
students, often ascribed to the prevalent lecture format of science classes, the lack of dialogue with instructors, a focus on grades, and the need to develop thinking and reasoning in students, has been acknowledged for more than a century (Dutch, 1996, Howe, 1892, Smith, 1955). These reports are quite uniform in their critique of the current situation and recommendations. These recommendations focus on five general areas: content and curriculum; pedagogy and assessment; development of student skills in
written and spoken communications, interpersonal skills, and problem solving and critical analysis; scientific literacy in citizens, and the potential of computer-aided instruction to support important educational goals. Reforms are particularly important for introductory courses, which are typically terminal science classes for many undergraduates (Stout, 1994). The perceived dullness or complexity of the material, a lack of concrete applications, and preconceptions among both students and instructors can make introductory science classes difficult for non-science majors and can lead to lower retention rates of science majors (Delaughter, 1998).

Introductory sciences are our best chance to increase scientific literacy of college students (Abd-El-Khalick, 2000, Laugksch, 1996, Miller, 1998). Scientific literacy is important for the health of a democracy in an increasingly technological society, where citizens are being asked to participate in important issues such as developing solutions to pressing environmental problems (Miller, 1998).

While many of these reports suggest the potential of authentic inquiry to support student learning, there remains a great need for additional research on learning issues (e.g. misconceptions, poor mental models, reasoning errors) associated with learning about complex earth systems. Likewise, there is a need to assess the implementation of authentic inquiry in various classroom contexts, and develop additional assessment techniques and instructional materials that support learning. Finally, there is a need to establish whether student learning issues concerning complex earth systems are an adequate model of similar cognitive issues expressed by experts, policy managers, or stakeholders involved in developing solutions to environmental problems. If the two groups exhibit similar reasoning errors and misconceptions, then educational research in the earth science has an important new application.

IMPLICATIONS

Development and implementation of effective environmental policy that addresses the most pressing issues involving the relationship between human society and the earth will require direct involvement by all stakeholders. It is likely that these people will face serious difficultly in understanding the complex nature of earth systems. Educational research focused on undergraduate student learning about complex earth systems can likely develop important insights that can be used to serve two distinct goals: improve undergraduate earth science education and address stakeholder learning issues during environmental problem solving.

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FIGURE CAPTIONS

Figure 1. Two adjacent watersheds - the Guadalupe and San Antonio - and major underlying aquifers - the Edwards and Carrizo-Wilcox are the focus of the proposed Texas Hydrologic Observatory (http://www.txh2o.org/). Watersheds are examples of regional earth systems.

Figure 2. NASA's Spaceborne Imaging Radar- C/X- band Synthetic Aperture imaging radar image of the Mississippi River in Mississippi, Arkansas, and Louisiana. The image highlights the spatial patterns of fluvial sediments along the river, which influence the dynamics of groundwater-surface water interactions.

Figure 3. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite captured this image of phytoplankton blooms off of the coast of Honshu, Japan's main island, on May 4, 2005. The complex spatial patterns of the phytoplankton reflect both biological growth and transport of the organisms and nutrients by ocean currents.

Figure 4. Conceptualization of authentic inquiry as a set of activities focused on the scientific exploration of a question or theme with the development and manipulation of internal models as the central cognitive activity.