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Understanding cause and effect in geosciences through systems modeling

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Neil Stillings (this volume) makes a very good point that resonates with my experience in upper-level undergraduate and graduate education: Students must be taught to tease apart complex earth systems, and a powerful method of doing so is systems modeling. I have attempted to use dynamical models of earth systems in my own research over the past 40 years and have coauthored two textbooks attempting to teach others how to exploit this very powerful method of knowing. My experience is that most students arrive at graduate school with a very limited understanding of the contemporary scientific method (by which I mean the earth scientist's way of gaining knowledge). This is revealed in their Ph.D. candidacy exams at The Pennsylvania State University, where they are required to write two research proposals without the help of their advisor. Our entering students often think that the best approach to gaining predictive knowledge is to collect a bunch of random observations and then look for linear correlations that can be interpreted as cause and effect. As Stillings points out, few are aware that they are unconsciously overvaluing confirmatory evidence and not appreciating that complex earth systems usually contain long-distance delayed feedbacks that make determining cause and effect devilishly difficult. A variant on this strict induction is exploitation of a new method or field area; i.e., "We have a new method to measure strain, and no one has ever used it in the Caucasus." To our graduate students that would seem to be justification enough for spending taxpayers' money, and sometimes it is. We all know the story of the discovery of magnetic stripes off the West Coast of North America: A ship mapping seamounts for the U.S. Navy also tows a magnetometer on little more than a whim and discovers an important indicator of plate tectonics (Menard, 1986, p. 72). However, much of the time, random data collection is wasted money. As Darwin allegedly said, "A fact neither for nor against an hypothesis is meaningless."

The fact is that contemporary earth science uses a variant of the scientific method given in chapter 1 of high school and college science textbooks. Models, particularly quantitative models, now play a pivotal role for us, just as they do for one of the "other" historical sciences—astrophysics. Astrophysicists cannot conduct physical experiments of galaxies colliding in the laboratory, for example, so they substitute space for time when imaging the heavens, and they rely strongly on complex numerical models simulating the fantastical processes of galaxy formation. Space is substituted for time to develop a temporal sequence of galaxy interaction because this temporal evolution is what their models predict. If the model output fits the temporal sequence of photographic plates, then the model becomes the best estimate for how the universe works. I would argue that philosophically at least, that is precisely what we earth scientists now do. Our models are physical-mathematical descriptions of temporal/spatial changes in important geological variables, as derived from accepted laws, theories, and empirical relationships. They are "devices that mirror nature by embodying empirical knowledge in forms that permit (quantitative) inferences to be derived from them" (Dutton, 1987, p. 1). We use them to rationalize the information coming to our senses, to tell us what the most important data are, and to tell us what data will best test our notion of how nature works as it is embodied in the model. We use models to state our formal assertions in logical terms and use the logic of mathematics to get beyond our limited intuition.

The important role that models play in contemporary earth science is recognized by the National Science Foundation (NSF). Calls for proposals and funding panels increasingly require hypothesis-driven science and, in particular, tests of those hypotheses using quantitative models. It is toward this end that NSF supports such community modeling enterprises as the Community Surface Dynamics Modeling System (CSDMS; http://csdms.colorado.edu/wiki/Main_Page) and the Computational Infrastructure for Geodynamics (CIG). CSDMS and CIG are large national efforts to use models to drive our collection and interpretation of data and to test hypotheses. As an example, consider the Chicxulub extraterrestrial impact event at the end of the Mesozoic Era that killed off the dinosaurs. It is probably the

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most famous hypothesis in historical geology, at least from the public's perspective, yet how are we to test it? To work through the specific details of what happened and to predict the consequences of such an uncommon event are not easy tasks, because the physical and chemical processes are operating in a pressure-temperature state all but impossible to obtain experimentally. It is precisely these cases that benefit most from numerical simulation. Gisler et al. (2004) derived a model simulating a 10-km-diameter iron asteroid plunging into 5 km of water overlying 3 km of calcite, 7 km of basalt crust, and 6 km of mantle material. The set of equations was solved using the SAGE code from the Los Alamos National Laboratory and Science Applications International Corporation, developed under the U.S. Department of Energy's program in Accelerated Strategic Computing. Their model contained 333,000,000 computational cells and used 1024 processors for a total computational time of 1,000,000 central processing unit (CPU) hours on a cluster of HP/Compaq personal computers (PCs). The results provide interesting testable predictions beyond the abilities of anyone's intuition, and we can rest assured that energy and mass are conserved. It is important to note that the impact model is an extreme case; simpler models are equally valuable. For example, consider the role that erosion plays in the tectonics of orogenic belts. The key idea here is that two-sided, frictional orogenic wedges reach a steady state (at least in theory) in which the tectonic mass flux into the wedge is balanced by an erosional mass flux off the top. A simple model based on conservation of mass in the orogen, critically tapered-wedge mechanics, and a first-order rate law of erosion provides deep insight into orogen behavior in the face of changes in accretion rate and climate (Whipple, 2009). Among other counterintuitive results, one discovers that the time it takes for an orogen to reach a new steady-state width and height does not depend upon the size of the orogen.

I have long puzzled over how to train students in this new scientific method. Even when our students can name the reservoirs in a system and have some notion of the processes that transfer mass or energy among reservoirs, they are poorly trained to grasp the notions of small inputs leading to large responses, jumps to new equilibrium states, and emergent properties arising from multiple, interacting feedbacks. Studying other people's models or using canned models like STELLA® may help. However, the only effective method I have found is to have graduate students learn to build their own models of earth systems. Only in this way do they develop the deep intuition needed to avoid inadequate transport laws, poorly constrained coefficients ("fudge-factors"), and feedbacks so complex that all insight is lost.

The value of the article by Stillings is that he doesn't just complain (as admittedly, I have here), but proposes a "complexity curriculum." This curriculum exploits models and modeling to teach students key concepts like feedback, emergent phenomena, multiple equilibrium states, and multiplicity of causes. This approach should go far to reconcile our earth science pedagogy with actual research practices.

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