Teaching quantitative skills and integrative thinking in earth sciences using object-oriented computer models

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Students studying Earth sciences often struggle with the quantitative aspects of the field and also with the fundamental interconnectedness between both different conjugate fields and different specific processes. Both of these issues have been addressed as part of a third year option course entitled *Advanced Topics in Sedimentology* by using the object-oriented modelling computer programme STELLA. Students are presented with mathematical concepts in an easily understandable way and are directed through practical activities designed without a single correct answer in mind, emphasising conceptual understanding over rote factual recall. By using a predict-perform-reflect pedagogical model, student learning is iterative and progressively harder problems may be introduced, culminating in open-ended problems that require students to integrate both existing knowledge and their new understanding gained from the earlier modelling exercises.

Introduction

Two fundamental pillars of an undergraduate education in Earth science are (1) integrative thinking (e.g. iSee Systems, Inc., 1999) and (2) numeracy, or quantitative skills (Macdonald *et al.*, 2000; Vacher, 2000; National Research Council, 1996). As a result, among our challenges as instructors are to teach quantitative skills to students who are often averse to 'math for its own sake', and also to impress upon them that they need to consider whole systems (the integration of the physical, chemical, and biological parts) rather than just the constituent parts.

The subject of this article is to examine a solution to both of these problems within the context of a third year option course (GL3210) in the Geology Department at Royal Holloway, University of London entitled *Advanced Topics in Sedimentology*. The solution that I have selected is to teach maths by 'stealth' and in a hands-on way using an object-oriented computer modelling programme.

Materials and methods

Rather than using more traditional, single-purpose models (e.g. Waltham, 1999) to address the twin issues of numeracy and integrative thinking, I selected the object-oriented computer modelling programme STELLA (iSee Systems, Inc.), which is available for both Macintosh and PC-compatible computers, and which has previously been used as an educational tool in a wide range of science courses (e.g. Levy and Mayer, 1999). The advantages to this are three-fold. First, by using a flexible modelling package, the same application can be used to solve a variety of different kinds of problems. Second, because the students build the models themselves, rather than being given a working programme, they have to understand why things are happening, thus removing the 'black box' from the process (Levy and Mayer, 1999). Third, Bice (2001b) has published a free access 'web book' of working STELLA models and up-to-date datasets that I have used as templates for the practicals in GL3210. STELLA has been used as part of GL3210 for two years so far, with students doing two practicals with it during the 2004 version of the course and three in 2005.

Pedagogical approach

I begin the first lecture on the subject of modelling Earth systems with a quotation that geochemical modeller Lee Kump (Pennsylvania State University) prefaces all of his conference presentations with, which is, "all models are wrong, some models are useful." The point of this is to emphasise that the students are looking to understand how things work, why certain processes are important, and how different parts of a system interact with one another rather than to 'make facts'. To put this idea into practice, rather than giving students fully functioning models, students must make their own computer models and enter all of the data after a brief introduction to the STELLA programme. As I will discuss further below, STELLA uses simple graphical elements to perform complex calculations. Because of this limited number of elements, most students 'pick up' the programme very quickly, and most of the questions quickly change from the 'how' variety to the 'why' variety.

The second important part of the pedagogical approach is to emphasise iterative learning (i.e., reflective practice) rather than 'correct' answers. The basic structure of each of the assessed problem elements is predict-perform-reflect. For example, in one practical the students use a simple energy balance model in which they are asked to model the effects of reducing solar insolation by 10%. The question in the practical reads as follows:

> "Make a prediction: how (and by how much) will the surface and atmospheric temperatures respond to the reduced insolation?"

Students then modify the model appropriately to reduce the solar insolation and run the computer programme, plotting their results graphically. The follow-up questions ask:

> "Was your prediction correct? Why or why not? Did you consider the effect on cloud cover? If you did not, be sure to look at that graph before you move on to the next question."

Thus, students are ultimately iteratively guided via a Socratic dialogue to certain conclusions and to notice certain important model effects, but only after they have attempted to understand the model and its processes on their own. Each practical ends with a 'can you simulate this?' scenario for the students to solve that has many different possible solutions. Thus, assessment is based upon the students using good logic to solve the problems and on demonstrating understanding rather than on trying to model a single correct scenario.

The third important part of the pedagogical approach is to integrate quantification (i.e., numeracy) using simplified graphical and textual descriptions rather than by using traditional mathematical notation. STELLA seamlessly incorporates differential equations and integration, statistical functions, and both discrete and graphical (i.e., continuous) inputs. As an example of how a differential equation can be inputted into STELLA, if I wanted a simple way to describe how temperature changes in response to changing atmospheric CO2 levels the following equation could be used:

$$\frac{dx}{dt} = k(y - 280) \qquad (1)$$

where dx/dt is the change in temperature (x) through time (t), k is a constant based on the relationship between warming and

CO_2 levels, and *y* is the measured atmospheric CO_2 level. The same equation in STELLA 'language' is longer, but much more straightforward to understand for students:

$$\frac{dTemp\_surface}{dt} = CO_2\_Temp\_rel(CO_2\_atm - 280) \qquad (2)$$

where it is clear that the surface temperature must increase for any atmospheric CO_2 level above 280ppm (the pre-industrial level). By having named variables that correspond to graphical elements, confusion among students about which "x" they are talking about is minimized while at the same time clarifying the relationships between different variables.

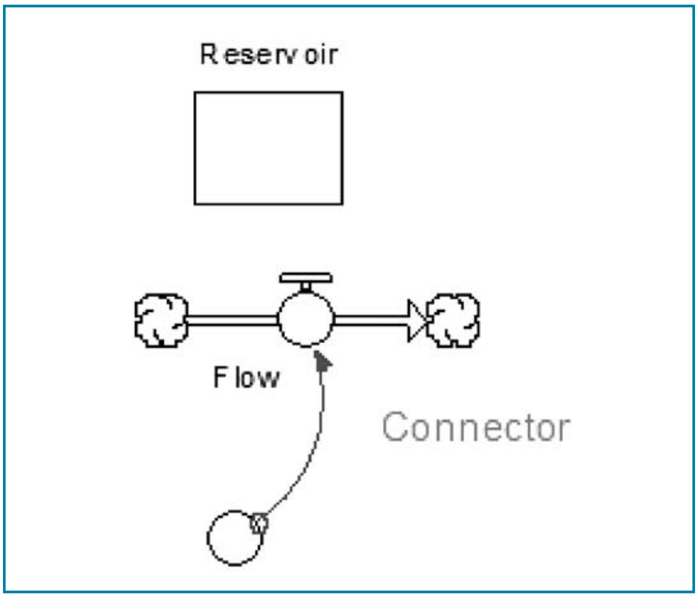
Models

Models constructed in STELLA use a combination of graphical elements and a simplified mathematical interface (as described above) to simulate complex systems. STELLA is particularly good at simulating dynamic systems that have a time dependence (Bice, 2001; 2001b), that is, at describing both final results and also the physical and chemical processes that produced the results. In GL3210, students construct three separate models depicting the rock cycle, energy balance during a glaciation (simple climate model), and the carbon cycle during glacial conditions. In the 2005 version of the course, students were also given a working soil moisture model to manipulate as a formative assessment. Their responses to these different approaches will be discussed below. For the remainder of this section, I will discuss the elements that make up a STELLA model and then present one of the models used in GL3210 in greater detail to discuss how it incorporates the three pedagogical goals described above.

Model Elements

There are four basic model elements (Fig. 1): reservoirs, flows, converters, and connectors. Reservoirs are essentially like bathtubs, in that material can flow both in (via the tap) and out [via the drain]. Flows are used to move material between reservoirs and to control the rate of material moving between two reservoirs. Converters are used to modify the rates of materials, to examine changes in a reservoir, or for any other mathematical operation. Connectors are used to make one element dependent on another. The directions of the arrows are important; material flows from left to right in the flow shown above, and the rate of that flow is dependent on the converter below it.

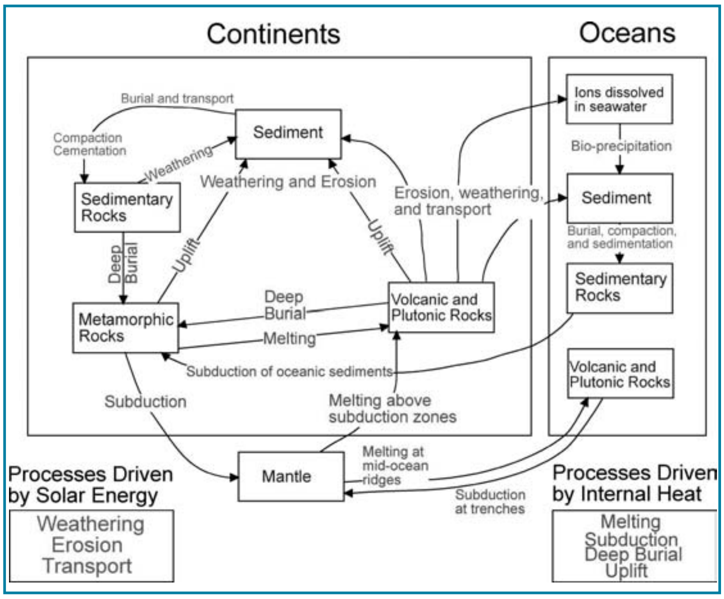
Figure 1. Model elements in the STELLA environment



Example of a model used in GL3210

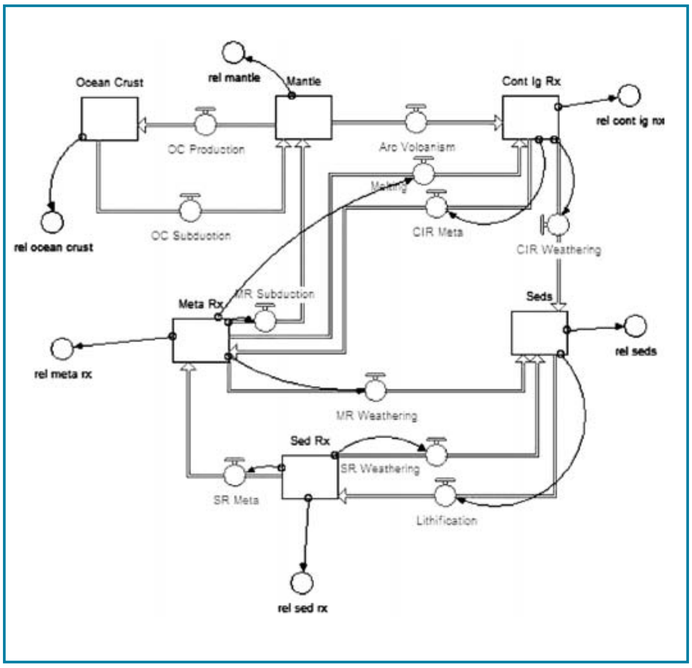
The first model that students build using STELLA is of the Earth's rock cycle. Within the context of the course, this is an important topic because GL3210 has two main emphases: (1) the inter-connectedness of processes and systems on Earth and (2) the role of climate in a variety of sedimentary environments and processes. Both of those concepts are central to and demonstrated by the Earth's rock cycle. In the practical, students are first presented with a cartoon depicting the processes that they will be asked to model (Fig. 2) and asked to identify which parts of the system are most intimately inter-connected.

Figure 2: Schematic cartoon of the Earth's rock cycle. Modified after Bice (2001b)



After this, the students are introduced to the model elements and given a few basic tasks (making a graph, etc.) to familiarise them with the STELLA environment before they build their own model. The rock cycle model is a closed system mass-balance model (i.e., no 'new' rock may be created and no rock may be 'lost'). Whilst upon first glance the model appears somewhat complex (Fig. 3), it is actually fairly simple because there are just six reservoirs and most of the reservoirs are not directly connected (i.e., they may not exchange material directly). For example, the continental igneous rocks reservoir (Cont_Ig_Rx) may receive material from the mantle (but not return it), may send or receive material from the metamorphic rocks and sediments reservoirs (Meta_Rx and Seds, respectively), but not at all from the ocean crust (Ocean_Crust) or sedimentary rock (Sed_Rx) reservoirs (Fig. 3). Once the 'picture' of the model is constructed, students must fill in data on initial values and rates and consider two important concepts: (1) steady-state behaviour and (2) dimensionless numbers. A system in steady-state or a model in steady-state is one in which the mass (or energy, or

Figure 3. Simple rock cycle model constructed in the STELLA environment



money, etc.) entering a part of the system is exactly matched by the mass leaving that part of the system, and is a necessary condition for modelling of this type (Fig. 4a; Zhu and Anderson, 2002; Bice, 2001) before experiments to examine changes in the behaviour of the system may be undertaken. Dimensionless numbers are scale-independent. This allows relative rather than absolute changes to be examined. By using dimensionless numbers to plot the results, all of the reservoirs, regardless of their initial size, may be plotted on the same scale (Fig. 4a-b).

After the students have constructed working models, the final step before the students begin to experiment is to ask them to consider how the model actually works and what changing an individual part might do. Once students feel that they have a conceptual 'handle' on how the model works, they are directed through a series of experiments that are progressively less prescriptive, culminating in an entirely open-ended scenario. First, the students consider the role of response time in the system using the predict-perform-reflect model described in the pedagogic approach section above, with the emphasis on integrating aspects of their knowledge from previous courses. For example, the text of the first experiment is as follows:

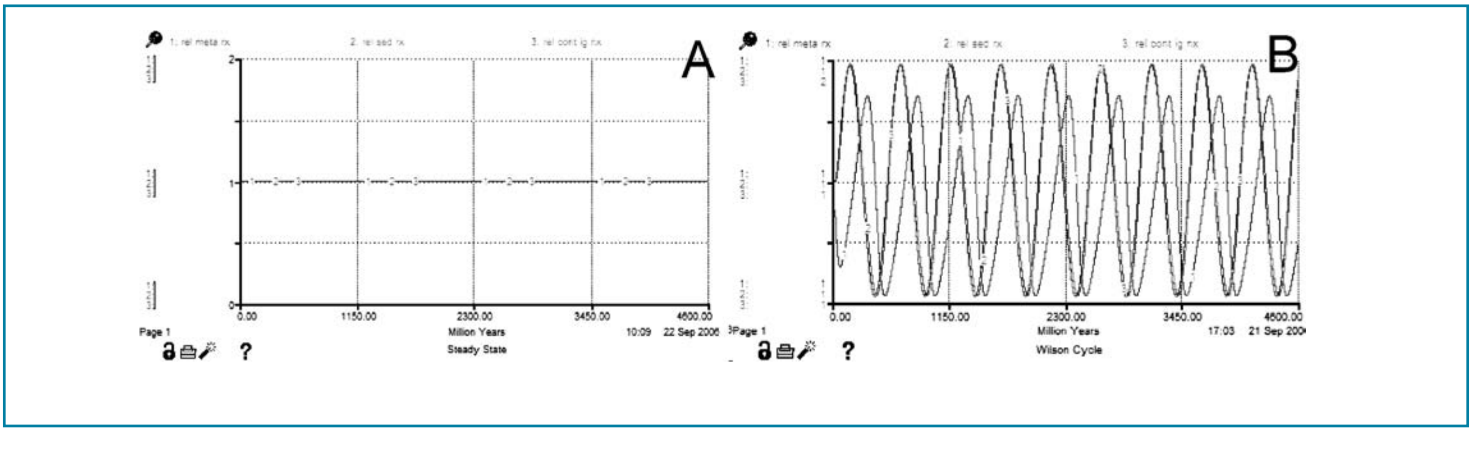
> Increase the initial amount of the Continental Igneous Rocks reservoir by 50%. To compensate for this change (i.e., obey mass balance), we will adjust the Mantle by the same amount. How will you do this? What process in the real world could cause this type of change? Before you run the model, answer these questions: Which of the reservoirs will be affected? Will the system return to a steady state? Run the model for a period of 5 billion years [50 time units] with a time step of 0.1 and the Euler method of integration.

These basic experiments are followed up by more complex concepts involving changing the rates of processes and integrating plate tectonic forces. For example, they are asked to use a simple function (sine wave) to examine cyclical changes in plate tectonic forcing (see resulting graph in Fig. 4b) for which there is a sound physical basis in the form of the Earth's long-term supercontinent cycle ('Wilson' Cycle).

The second way that students use tectonic forcings is to examine the role that declining heat flow, as the heat left over from the Earth's formation is lost to space, plays in rock cycle processes. In addition to reinforcing this important concept from first and second year courses in geology, this part of the practical also introduces the students to the use of graphical (i.e., discrete) inputs. Because most of the data in geology is discrete (one data point for a given time) rather than continuous (e.g., temperature monitoring at a weather station), much of our understanding of different processes is based on interpolation between the discrete data points. The students are asked to interpolate a reasonable curve to fit a limited data set and then to use the curve that they have generated as an input into the model. This section tests the students' understanding of the underlying concept (i.e., heat loss), their ability to interpolate from limited data, and also their ability to integrate different types of data.

The final part of the practical is open-ended (pedagogical goal #2, iterative learning) and presents students with a 'how would you model this?' scenario in which students are directed to

Figure 4. Model results. A) Model at steady-state. B) Model results of a simulation of the 'Wilson Cycle' spanning 4600 times units (= 4.6 billion years). Note the different scale bars on the y-axis and the time lags between some of the dimensionless measurements of rock mass.



formulate and carrying out a plan to model the formation and evolution of the Earth. Though there is no single correct answer, this part of the practical tests the students on two things: (1) to recognize what the initial conditions on early Earth must have been; (2) to figure out logically and creatively how to modify the model to test their hypothesis or hypotheses until their model simulates the Earth's history, including reaching its present-day steady state. As with other parts of the practical, the assessment is based on students using sound logic and integrating both the underlying concepts from previous courses in geology and also what they have learned from the previous experiments in this practical.

Student feedback

Students both years began the practicals with some reticence because they represented something completely new for all of them. In spite of this, the vast majority of the students both years took to this approach quite readily. In 2004, seven of nine students described these practicals as "extremely useful" or "very useful" in course feedback, and for 2005, 11 of 13 students gave similarly positive remarks. One of the differences between the 2004 and 2005 versions of the course is that the 2005 course also included a STELLA model used as a formative rather than summative assessment. That model was given to the students fully-functional. As part of the course feedback, students were asked if they preferred to be given working models or if they preferred to construct their own, 10 of 13 indicated that they preferred to construct their own, and 11 of 13 felt that they understood the material better from the practicals where they had to construct their own model than from the one in which they only manipulated an existing model.

Conclusion

With courses like this one, explicitly designed to make mathematics 'less scary' while building on students' knowledge base from a number of courses, we should be able to prepare our students better for a variety of future endeavours whether in the Earth Sciences or in some other field. By emphasizing integrative systems thinking (iSee Systems, 1999), coupled with both directed (e.g. Levy and Mayer, 1999) and open-ended problem solving (e.g. Bice, 2001; Walker, 1991), students' understanding of both conceptual and factual parts of the Earth Sciences should be enhanced. Their quantitative and logic (problem-solving) skills will also be developed in ways that will be broadly applicable to them both in other Earth Science courses and in their professional lives.

Acknowledgements

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References

Bice, D. M. (2001), Using STELLA models to explore the dynamics of Earth systems: experimenting with Earth's climate system using a simple climate model, *Journal of Geoscience Education*, 49: 170-181.

iSee Systems, Inc. (1999), Introduction to systems thinking with STELLA. Lebanon, New Hampshire (US): iSee Systems.

Levy, J., and Mayer, L. (1999) Systems modelling of non-equilibrium chemical reactions using STELLA, *Journal of Geoscience Education*, 47: 413-419.

Macdonald, R.H., Srogi, L. and Stracher, G.B. (2000), Building quantitative skills of students in geoscience courses, *Journal of Geoscience Education*, 48: 409-412.

National Research Council (1996), *National Science Education Standards*. Washington, D.C., National Academy Press.

Vacher, H.L., (2000), A course in geological-mathematical problem solving, *Journal of Geoscience Education*, 48: 478-481.

Waltham, D.W. (1999), *Mathematics: A Simple Tool for Geologists*, 2nd Ed., London: Blackwell Science.

Walker, J.C.G. (1991), *Numerical Adventures with Geochemical Cycles*. New York: Oxford University Press.

Zhu, C. and Anderson, G. (2002), *Environmental Applications of Geochemical Modeling*. Cambridge: Cambridge University Press.

Web Resource

Bice, D.M. (2001b), *Exploring the Dynamics of Earth Systems* (text/lab manual for STELLA modeling and Earth system science class) "Web Book" [http://www.geosc.psu.edu/~dbice/DaveSTELLA/entrance.htm]

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