Modeling the Global Carbon Cycle with STELLA

Dave Bice
Geology Department
Carleton College
Northfield, MN 55057
dbice@carleton.edu

A STELLA model of the global carbon cycle allows students to learn about the dynamics of this critical biogeochemical cycle through experimentation. The model is based on current best estimates of reservoir sizes and fluxes of carbon, including reasonable paramterizations of key processes. The model is fast and easily modified, enabling students to ask questions, make predictions, and find precise, numerical answers.

Preparing Students for This Modeling Exercise

BASICS

Students are first introduced to the concepts of modeling and the mechanics of STELLA through a variety of simple exercises such as modeling the flow of water in and out of a bath tub. A set of simple examples and background material on modeling with STELLA is available at my web site:
http://www.acad.carleton.edu/curricular/GEOL/DaveSTELLA/entrance.htm

CARBON CYCLE PROCESSES

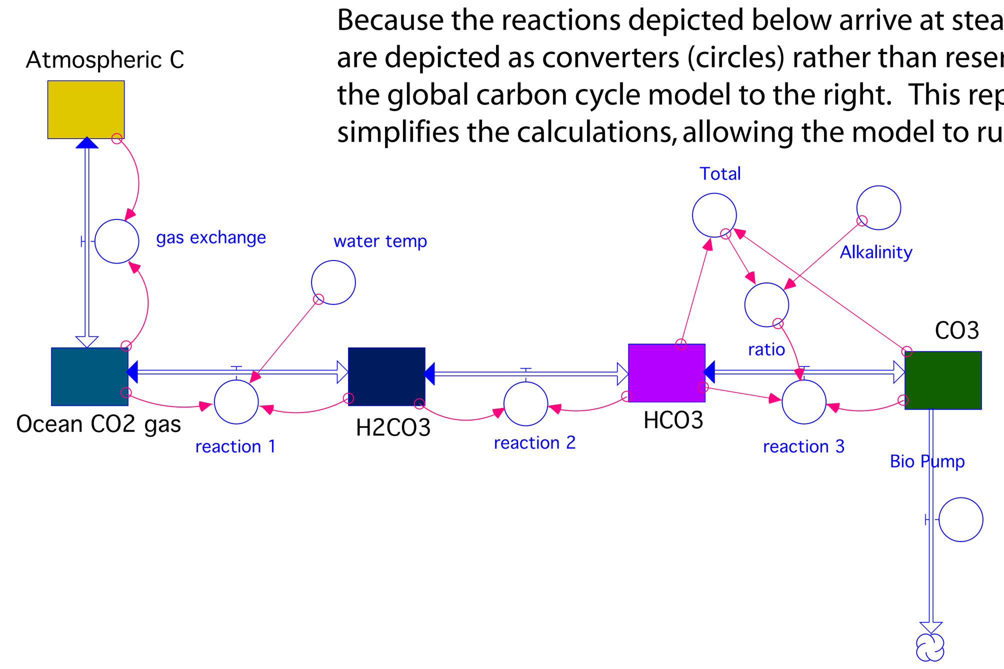
The web site listed above contains an introduction to the carbon cycle, including information about its recent history and the processes that transfer carbon from one reservoir to another. These processes are also described in terms of simple equations that are used in the model. Understanding the behavior of the carbon cycle, how it responds to various changes requires a clear understanding of how these processess are described in the model.

CARBONATE CHEMISTRY & OCEAN - ATMOSPHERE TRANSFER

The diffusive transfer of carbon between the ocean and atsmosphere depends on the CO_2 concentration in both the ocean and the atmosphere. The model calculates the CO_2 concentration of the oceans using a scheme based on Walker (1991). The carbonate chemistry is the most complex part of the model; a small-scale version of just the carbonate chemistry system can help clarify how this works.

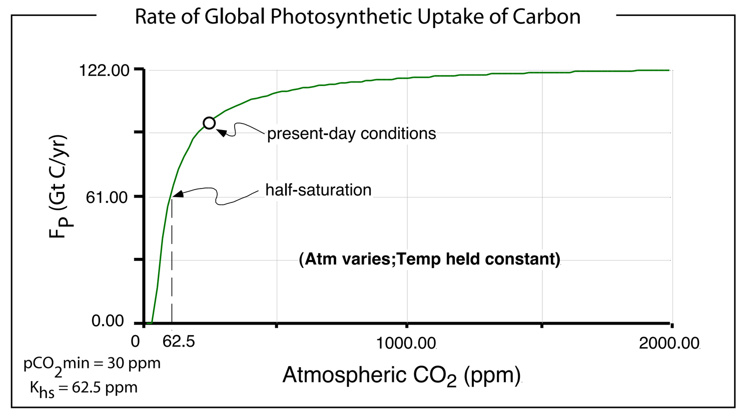
Carbon moves very rapidly between 4 inorganic oceanic reservoirs according to a set of equilibrium constants, temperature, alkalinity, and total carbon content. The adjustments are also driven by the need to maintain charge balance in seawater. The movement of carbon into the bicarbonate and carbonate forms accounts for the important buffering capacity of the oceans, allowing the oceans to absorb huge quantities of carbon from the atmosphere.

Because the reactions depicted below arrive at steady state so fast, they are depicted as converters (circles) rather than reservoir quantities in the global carbon cycle model to the right. This representation simplifies the calculations, allowing the model to run much faster.



PHOTOSYNTHESIS

The model represents photosynthetic uptake of carbon by land plants through an equation that is based on greenhouse experiments. The uptake of carbon varies as a function of both temperature and atmospheric CO2 concentration. The figure on the right shows how this flow varies with atmospheric CO2. Our present-day position on this curve is not too heartening — as the atmospheric CO2 rises, the rate of photosynthesis will increase less and less, and "greening" of the biosphere is less capable of slowing the build-up of atmospheric CO2.



The Global Carbon Cycle

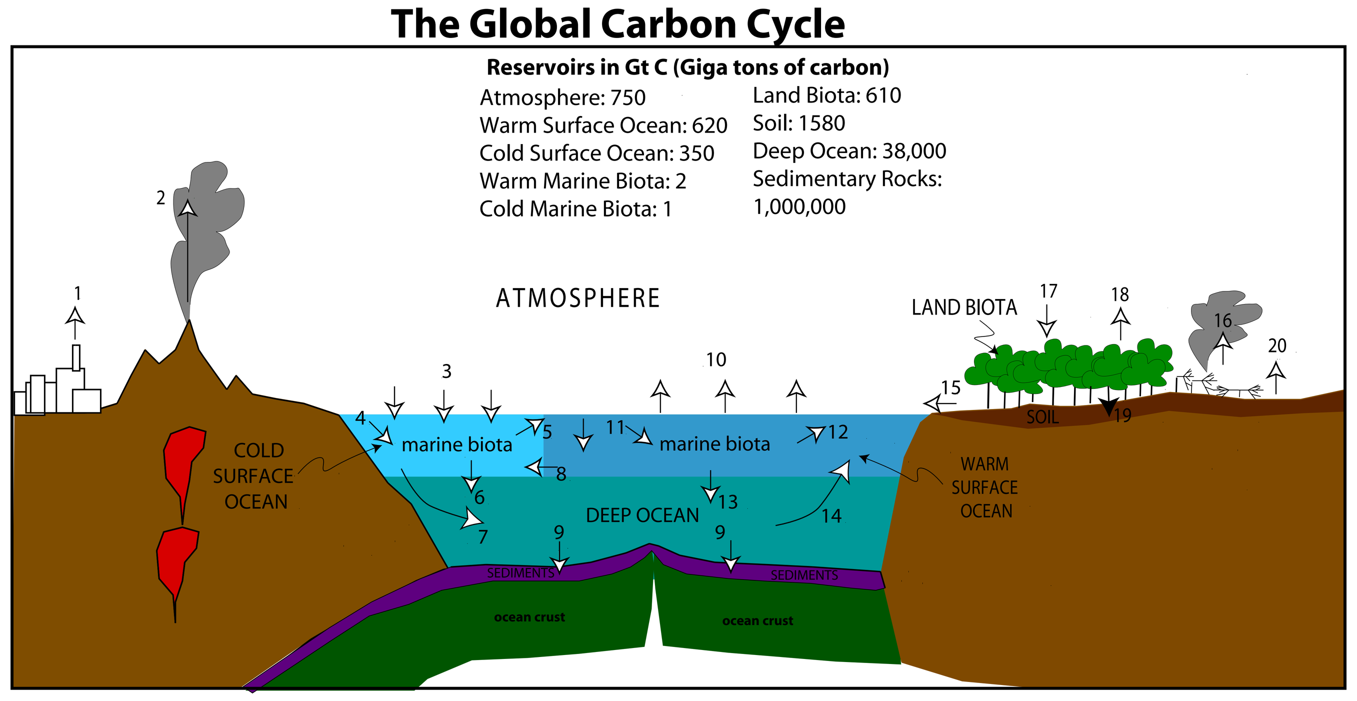
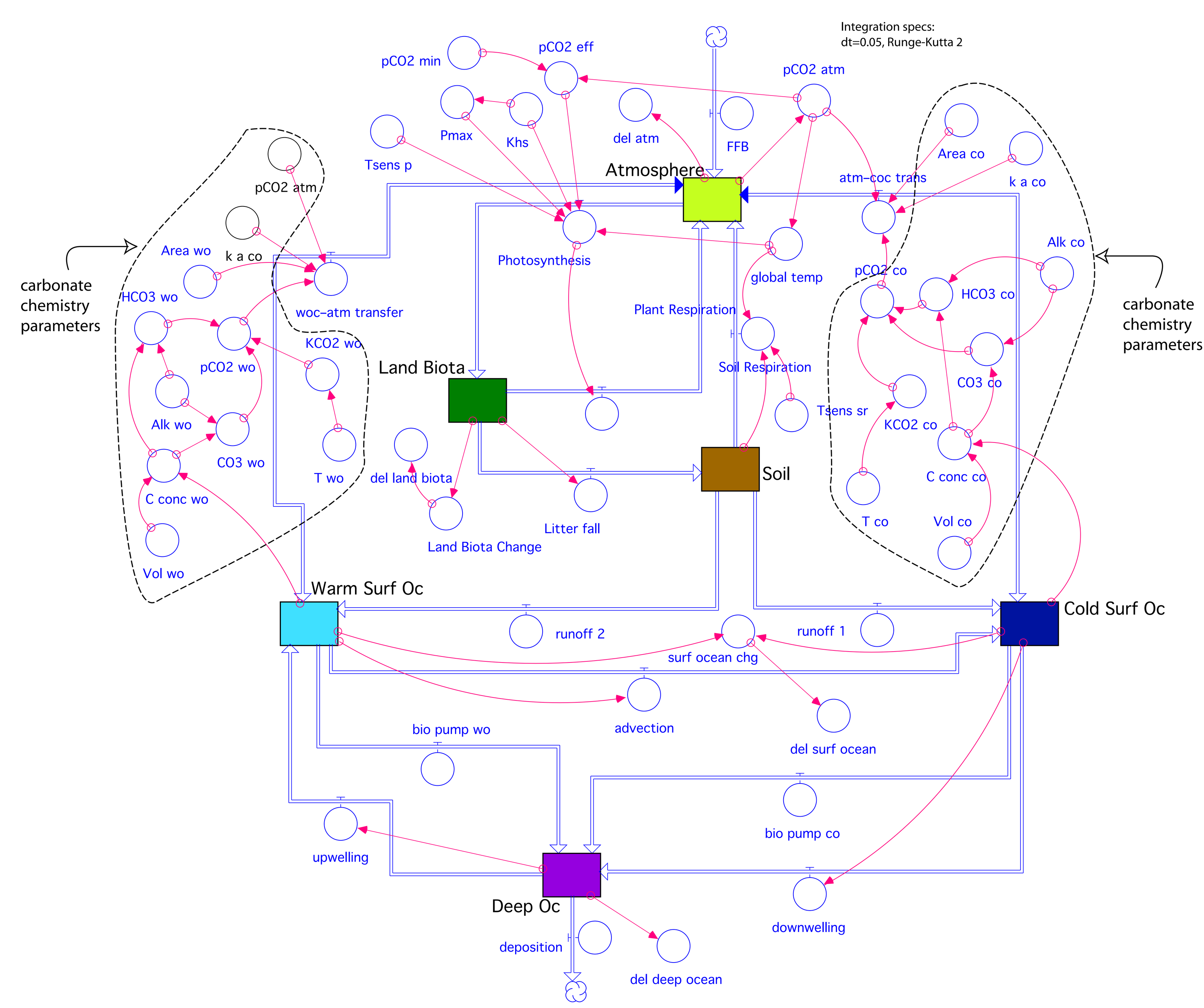


Figure 1. The global carbon cycle, as best estimated, in 1994. Data slightly modified from Siegenthaler and Sarmiento, 1995; Kwon and Schnoor, 1995.

Key to Flows:

1) Fossil Fuel Burning — 5 Gt C/yr
2) Volcanic Emissions — 0.6 Gt C/yr
3) Uptake of CO_2 by cold surface waters of the oceans — 90 GtC/yr
4) Photosynthesis of marine biota in cold surface waters — 18 GtC/yr
5) Respiration of living marine biota and rapid recycling of dead biota in cold surface waters — 14 GtC/yr
6) Sinking of dead marine biota (both organic and inorganic carbon) from cold water into deep water — 4 GtC/yr
7) Downwelling of cold surface water (mainly near the poles) — 96.2 GtC/yr
8) Advection (horizontal transfer) from warm to cold surface water — 10 Gt C/yr
9) Sedimentation on sea floor (both organic and inorganic carbon) stores carbon in sedimentary rocks — 0.6Gt C/yr
10) Release of CO_2 by warm surface waters of the oceans — 90 GtC/yr
11) Photosynthesis of marine biota in warm surface waters — 32 GtC/yr
12) Respiration of living marine biota and rapid recycling of dead biota in warm surface waters — 26 GtC/yr
13) Sinking of dead marine biota (both organic and inorganic carbon) from warm water into deep water — 6 GtC/yr
14) Upwelling of deep water (at equator and along edges of continents) — 105.6 GtC/yr
15) River runoff transfers carbon from the land to the sea — 0.6 Gt C/yr (2/3 to warm ocean, 1/3 cold)
16) Deforestation and land clearing releases CO2 into the atmosphere — 1.5 Gt C/yr
17) Photosynthesis of land biota — 110 Gt C/yr
18) Respiration of land biota — 50 Gt C/yr
19) Litter fall and below-ground loss from plant roots transfers carbon to the soil — 60 Gt C/yr
20) Respiration of micoorganisms in the soil releases CO2 into the atmosphere — 59.4 Gt C/yr



Experiment 1. Comparing the Model with the Real World

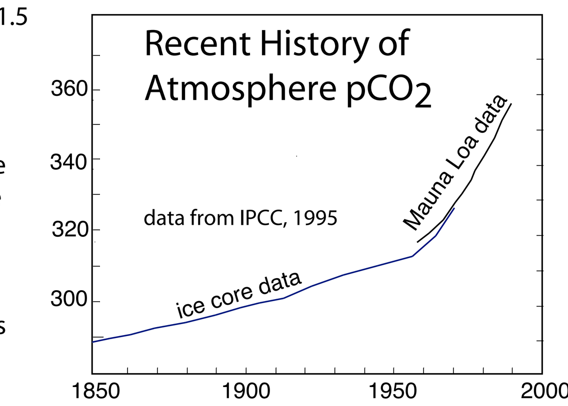
This global carbon cycle model can be used for an important experiment in which we take advantageof humankind's experiment with the natural carbon cycle. By running the model with the history of increasing anthropogenic emissions, we can compare the model with the present state of the carbon cycle to see whether or not the model gives results that are consistent with the real world carbon cycle. This test of the model will give us some sense for how much attention we should pay to the actual numbers generated by our model. It should be stressed, however, that even if our model gives results that are consistent with the present state, that is not a guarantee that our model captures the full complexity of the real system well enough to allow us to confidently predict what will occur in the future. Part of the reason for saying this is that there may very well be thresholds in the natural system, separating realms of very different behavior. For example, it might be the case that with another degree of warming, downwelling may begin to decline rapidly, severely limiting the amount of carbon that the oceans can absorb from the atmosphere.

Use the emissions history given below for fossil fuel burning and land-use changes.

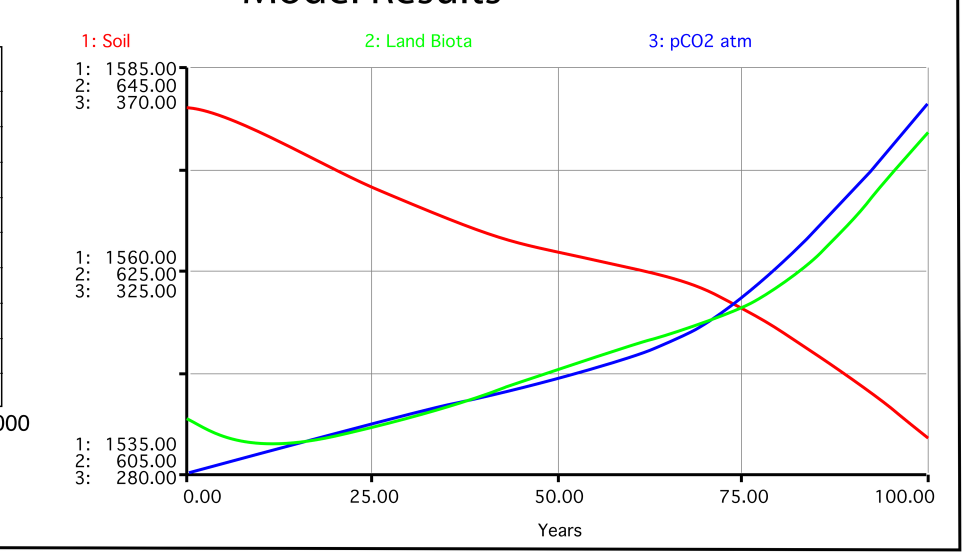
Year	Fossil Fuel Gt C/yr	Land-Use GtC/yr
0	0.350	0.6
10	0.525	0.6
20	0.805	0.65
30	0.959	0.65
40	1.078	0.7
50	1.300	0.7
60	1.638	0.8
70	2.586	1.1
80	4.084	1.3
90	5.292	1.25
100	6.098	1.5

Partition the land-use changes into 75% tree-burning and 25% soil disruption. This can be done by first creating a converter called Land-Use Emissions and make it a graphical function of time, entering the above data, then creating two new converters nearby, labeling one Forest Burning and the other Soil Disrupt. Draw connector arrows from Land-Use Emissions to each of these new converters and then define each of them as the appropriate fraction of Land-Use Emissions. In comparing the model with the real world, you should pay attention to the ending model values for the atmosphere reservoir and the rates of change for the atmosphere and ocean, which can be compared with the real world.

The model results closely match the observed record for the same time period. This means that the carbon cycle model generates meaningful results so long as there is not some kind of non-linear mode switch that becomes important in the future.



Model Results



Experiment 2. Looking into the Future

In these experiments, we start off with the history of the last 100 years and then project different emissions scenarios into the next 100 years.

a) Business-as-Usual

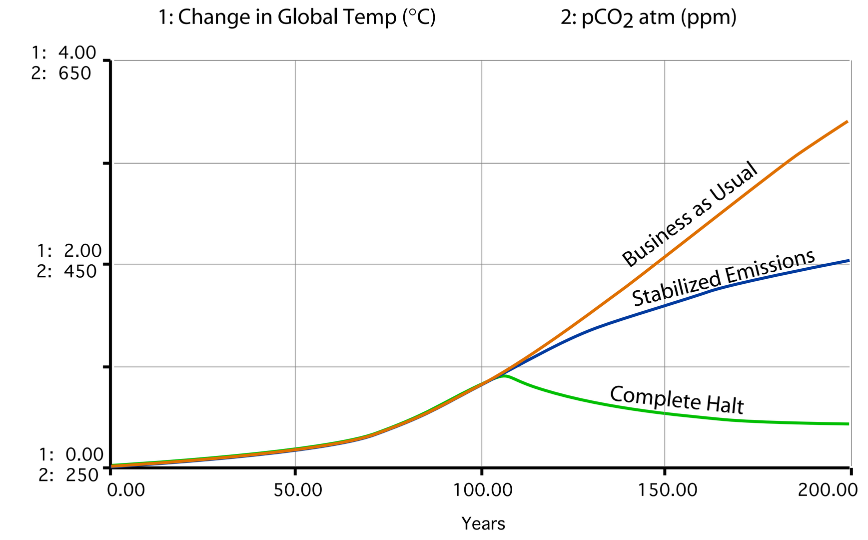
What will happen in the future if we continue on our present course? Continuing on our present course means projecting the curve of fossil fuel emissions using the most recent slope; this is sometimes called the business-as-usual scenario. At present rates of consumption, we should run out of liquid petroleum before the end of this time, but we will still have plenty of coal reserves on hand that could be utilized, so the emissions scenario we will use is not unrealistic, although it is not the most optimistic.

b) Stabilization

Here we keep the emissions steady for the next 100 years. This scenario implies that through some combination of dramatic changes in the population growth rate and fossil fuel consumption per person, the emissions are kept constant at the present rates.

c) Reduction

Now let's imagine that globally, we go on an incredible austerity program and/or that there are amazing, un-dreamed of technological advances such that our emissions drop to zero. Clearly, this is the most unrealistic of the scenarios explored here, but it defines one end of a spectrum of scenarios, so it is a good scenario to explore -- it helps place some boundaries on what the future could hold.



Benefits of Modeling the Carbon Cycle

Students effectively learn about the dynamics of the carbon cycle and the important processes and feedbacks through experimentation — they can quickly explore a wide range of questions and gain an intuitive understanding of what is otherwise a very complex system. The resulting understanding goes far beyond what most students get by considering a simple diagram.

Most students find these kinds of exercises exciting, especially when they find out that the model does a very good job of representing the recent history — this provides a sense that they are working with something pretty sophisticated (and they are).

The experiments are best suited for small group work; these groups commonly are very active centers of discussion.

In the ideal use of this model, students take the time to go through all aspects of the model construction, which forces them to integrate some basic chemistry, biology, and oceanography.

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