# Systems Thinking and Modeling Climate Change

Amy Pallant, Hee-Sun Lee, and Sarah Pryputniewicz

You know the effects of the proverbial butterfly flapping its wings. But what about an automobile driver? Can a single driver's actions affect Earth's climate? Earth's systems are complex and full of surprising interdependencies. How do we help students understand those complexities and seek answers to the automobile question, considering cumulative and global effects? One approach is to emphasize systems thinking in science education.

Systems thinking suggests that you can best understand a complex system by studying the interrelationships of its component parts rather than looking at the individual parts in isolation. A systems approach helps students understand interrelated elements, feedback loops, and in this case, a focus on the whole Earth (Center for Ecoliteracy 2012). With ongoing concern about the effects of climate change, using innovative materials to help students understand how Earth's systems connect with each other is critical.

## Modeling Earth's climate

This article describes the High-Adventure Science online climate change curriculum called "Modeling Earth's Climate" developed at the Concord Consortium (see "On the web"). This free, innovative curriculum incorporates dynamic computer models developed in the NetLogo modeling environment (see "On the web") that enable students to visualize the complex interactions related to climate change science. The

models are designed to allow students to change variables to help them discover how the individual parts relate to the whole system. While we don't expect the students to understand every single variable that affects climate change, this approach helps students make sense of human effects on Earth's system.

## The models
Our models are ideal for exploring Earth system science and human impact on the Earth. The models simulate changes in a system and are based on mathematical algorithms that approximate fundamental physical laws (Pallant and Tinker 2004). Research shows that computational models and simulations allow students to understand through exploration the behavior of systems that are difficult to understand by other means (Feurtzeig and Roberts 1999; Horwitz 1999). Much as scientists do, students can experiment with models by controlling conditions at the start (parameters) and during a run; they can explore cause and effect because they can observe the changes in the models that emerge from fundamental science-based rules. The models have vivid graphics and run quickly, so students can run multiple experiments to gain insights by carefully observing changes to the system. Thus, students can learn both content and the process of science by experimenting with the models.

In the Modeling Earth's Climate curriculum students begin by using a computer model to explore the effect of carbon dioxide on global temperature. The model helps students see how carbon dioxide traps infrared radiation, in turn increasing the temperature. Students can increase or decrease $CO_2$ amounts in the model and

observe how the changes affect the system by interpreting the output graph to the left of the model (Figure 1). By experimenting with extremes—adding lots of $CO_2$ or removing most of the $CO_2$—and paying attention to the resulting graph, students discover for themselves the relationship between atmospheric carbon dioxide and temperature.

Students encounter increasingly complex models as they proceed through the curriculum and shift their focus from the parts to the whole. They learn that the actual temperature increase on Earth is greater than what would be expected if only carbon dioxide levels were considered. The curriculum introduces new variables, such as water vapor, into the model and asks students to explain the relationships among the interrelated parts of the system. Students can, in this case, explore the effect of two different greenhouse gases and discover the interrelationships among the levels of $CO_2$, the amount of water vapor in the atmosphere, and the effects on atmospheric temperatures.

## Feedback loops

Feedback loops can enhance or buffer changes that occur in a system. Positive feedback amplifies changes, and negative feedback tends to dampen changes (Science Education Resource Center at Carleton College 2003). In climate change, positive feedback accelerates temperature rise; negative feedback decelerates it. The Modeling Earth's Climate curriculum explores different feedback loops. For example, because ice is both light colored and reflective, sunlight that hits ice

bounces back to space, limiting warming. However, as Earth gets warmer, ice melts, revealing ocean or land, which are darker than ice and therefore absorb more of the sun's energy. This leads to more warming, which in turn leads to more ice melting, and so on in this positive feedback loop. In the curriculum, students can use a model to change the percent of ice cover or amount of greenhouse gases and correlate these changes to changes in Earth's temperature.

Another feedback loop highlighted in the curriculum is the effects of cloud cover on Earth's temperature. This, too, is a balance between sunlight reflected off clouds and away from Earth (a cooling effect) and infrared radiation from Earth absorbed by clouds and re-radiated into the atmosphere (a warming effect). In the model, students can change the amount of cloud cover and then analyze the output graph (Figure 2). (See Kahn, p. xx of this issue, for more about the effect of clouds on climate.) Finally, the curriculum also models the relationships among $CO_2$, temperature, and dissolved $CO_2$ in the oceans. Students can explore what happens to the level of $CO_2$ in the air and oceans as atmospheric temperature changes. Such feedback loops are complex in themselves and are even more complex when considered as part of an integrated climate system.

## Climate models are complex

Our best hope of understanding how global temperature changes over time, and how humans may be affecting it, lies in the climate models scientists have developed. Actual climate models are some of the most complex models in all fields

of science. Clearly, the curriculum models are much simpler, yet they provide useful tools to test student ideas, make predictions, and understand system thinking. Modeling Earth's Climate scaffolds student thinking by focusing on how the model represents parts of the system, the interactions within the system, and the model limitations. The curriculum does this by asking explicit questions around models such as "How does the level of carbon dioxide affect the level of water vapor in the atmosphere?" "How can you tell that a model is good?" "What kinds of tests can you run to assess the validity of the model?"

*A Framework of K-12 Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC 2012) states that models can be valuable for exploring a system's behaviors. By simulating climate in the past, scientists can see how well the models compare to real-world data and judge how they might predict the future. The High-Adventure Science curriculum also has students compare model output—and their own conclusions—to real-world data.

As students increase the complexity of the models, they move from a vague sense that "everything interacts" to more concrete examples of the physical, chemical, biological, and human interactions related to climate change outcomes emerging from the model. Embedded assessments ask students to describe explicitly the behavior of the system and its many interacting variables, as well as the cause-and-effect relationships in the system. For example, students must report how changes in the amount of ice covering Earth's surface can affect Earth's temperature. Student

responses to this question included: "The more ice coverage, the colder it will get because the sun's rays are reflected back out of the atmosphere," and, "When there is more ice, the ice will reflect all of the energy from the sun and therefore the Earth will be a lot less warm." This type of question makes students think about the interrelationships in the system. Asking students to explain the mechanisms of complex feedback loops also requires higher-order thinking about interrelated variables.

We have analyzed student pre- and post-test work for 260 middle and high school Earth Science and Environmental science classes. The test included items that focused on content and nature of science skills, consisting of multiple choice and short-answer questions. We concluded that students of all levels can improve their systems thinking modeled in our climate change curriculum. The test can be found on the High-Adventure website (see "On the web").

## Human interactions and the climate system

You can't study climate change these days without looking specifically at anthropogenic causes of change. *Climate Literacy, The Essential Principles of Climate Science* (U. S. Global Change Research Program 2009) states: "The overwhelming consensus of scientific studies on climate indicates that most observed increase in global average temperatures since the latter part of the 20th century is very likely due to human activities, primarily from increases in greenhouse gas concentrations resulting from burning of fossil fuels." (p. 6) This brings us back to our original set of

questions: Can a single automobile driver affect Earth's climate and how do we help students learn about the role of humans in changing climate? The High-Adventure Science curriculum includes opportunities for students to explore how human-produced emissions (based on burning fossil fuels) can change average Earth temperatures over time. Students test what happens when they increase human-produced greenhouse gas emissions and what happens when they reduce human-caused emissions. The level of emissions is one more variable in the complex system that is modeled. However, the model alone is not enough; students must also compare outcomes to real-world data. The curriculum has students analyze climate change based on ice core data (Figure 3), ocean atmosphere data, and the Keeling curve graphs of ongoing atmospheric change in $CO_2$ concentration, among others. Climate change science is complex, and students are not expected to master every detail through the curriculum. But greater comprehension does require systems thinking, namely the ability to understand how various components influence each other within a complex system, the models used to represent these systems, and-the interconnections among the component parts.

The Framework includes a broader range of ideas in Earth and Space science than previous efforts. Core ideas include focus on 1) Earth's Systems, 2) Earth and human activity, and 3) an understanding of scientific practices. Prominent in all three of these core ideas is climate change science. The Framework specifies that students should look at feedback loops, explore interconnected features of Earth's climate system, compare historic and present climate change, as well as study the ways in

which human activities relate to Earth's processes. The Modeling Earth's Climate curriculum strongly integrates these core concepts. (National Research Council, 2012, p 196-198).

## Conclusion

How we examine problems depends in part on our world view. With any system the whole is different than the sum of its parts. The High-Adventure Science Modeling Earth's Climate curriculum engages students in systems thinking, enabling them to construct their own knowledge on factors that influence climate change, compare it to data from the scientific community, and think critically about complexities of climate change.

*Amy Pallant* (apallant@concord.org) *is the principal investigator on the High-Adventure Science project, and Sara Pryputniewicz* (spryputniewicz@concord.org) *is a research assistant, both at the Concord Consortium in Concord, Massachusetts; Hee-Sun Lee* (heesun.lee71@gmail.com) *is a visiting assistant professor at the University of California, Santa Cruz.*

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expressed in this paper, however, are those of the authors and do not necessarily reflect the views of the NSF.

## On the web

Concord Consortium: *www.concord.org/projects/high-adventure-science*

NetLogo: *http://ccl.northwestern.edu/netlogo/*

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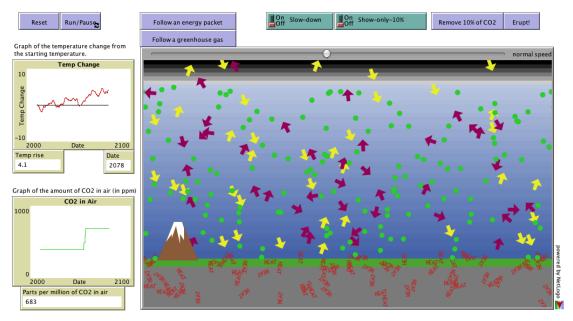
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*Figure 1: Climate Model. This model allows students to follow energy (represented by yellow arrows) from the sun as they interact with greenhouse gases (represented by green dots0 and the Earth's surface where they are reflected as infrared radiation (represented by red arrows) or absorbed as heat. Students can change the amount of $CO_2$ in the atmosphere As students increase the C02 the temperature increases as seen in the graph.*
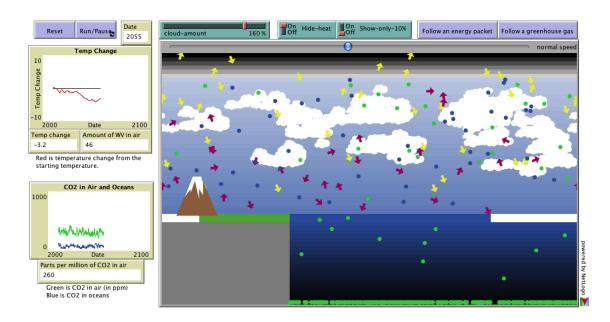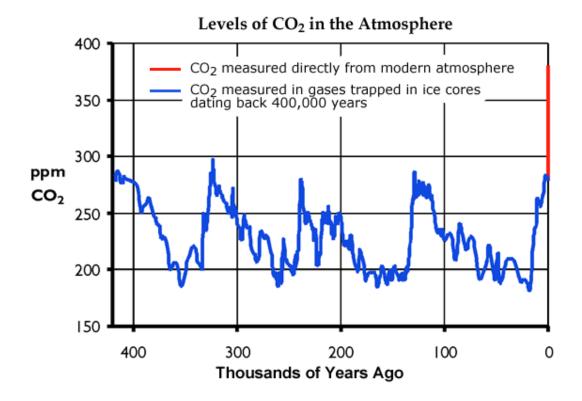
*Figure 2: This model allows student to change the cloud cover to see how an increase in clouds, in this case, lowers temperature. Students observe the relationship between cloud-cover, incoming solar radiation (yellow arrows), infrared radiations (red arrows) greenhouse gases (blue and green dots) and land, ocean and ice to help explain the resulting graph.*

*Figure 3. Atmospheric carbon dioxide concentration during the past 417,000 years.*
http://upload.wikimedia.org/wikipedia/commons/8/88/CO2-417k.png