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Earth Science

SPECIAL ISSUE

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Perspective:
Transforming Earth Science Education with Technology

By Amy Pallant

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When natural hazards such as floods, tornadoes, hurricanes, volcanoes, and earthquakes occur and impact our lives, we sit up and take notice. The truth, of course, is that everything in our lives is dependent on Earth. We rely on Earth's energy, mineral resources, fresh water, and atmosphere. The motion of Earth's plates is responsible for the land we live on as well as the recycling of carbon dioxide between the oceans and the atmosphere. But humans also impact Earth's processes. We pollute, burn fossil fuels, and deforest the land. These actions trigger climate change, soil erosion, a decrease in air quality, and the availability of drinking water.

The blue planet is big and Earth science education has a correspondingly big job to do. We need to help students understand Earth as a set of complex systems that are intricately interconnected. We also need to explain how Earth's processes affect people and, in turn, how people affect Earth's processes. Today's students are tomorrow's problem solvers, policymakers, and voters. We must ensure they have the knowledge about Earth's systems to be able to discuss and act on environmental and economic issues that affect our daily lives and our future.

More than other sciences offered at the pre-college level, Earth science education varies dramatically around the country. Earth science is commonly taught in middle grades (6-9), either as a separate course or as part of general or integrated science. In high school some Earth science topics may be included in environmental science or as an elective. This "orphan" status is due to the fact that Earth science was only formalized as a public school science in the 1960s, taking a back seat to the laboratory sciences of biology, chemistry, and physics, named in the 1892 Committee of Ten report that first recommended standardization of American high school subjects. Because Earth and space science (ESS) does not offer Advanced Placement credits, it is often skipped by students and dropped by states in favor of the three college preparation lab science classes. As a result, supporters of Earth science education have been forced to closely monitor the activities of state-level educational policymakers and school districts to prevent the elimination of these classes. The limited acceptance of ESS as a valuable science has been changing, though it still remains marginalized, considering the relevance and importance of the content taught in these classes.

Until recently, there has been little focus on Earth science pedagogy or educational research in Earth science teaching. The result is that Earth science is still taught in much the same way it was taught in the 1970s, for example, when there were few or no computers in the classroom. The typical approach to Earth science education is focused on memorizing facts related to Earth's structure, naming and classifying eras and periods, and identifying rock types. And the curricula rely on static illustrations and images, which limit students' understanding of Earth as a dynamic system. Earth science is almost never treated as a lab science, as most hands-on experiments with Earth phenomena are impossible, taking place over unimaginably long times far beyond students' perceptions. Students are thus unable to directly observe the emergence of Earth's phenomena. Instead, classroom activities use analogies to demonstrate Earth systems, generally employing materials such as Styrofoam to represent Earth's crust or modeling clay to explore metamorphism in ways that gloss over or underemphasize important aspects of these processes. Students are rarely given the opportunity to do their own sensemaking in Earth science, and thus do not develop deep understanding of the content.

New standards and new tools require new pedagogies

A Framework for K-12 Science Education and the Next Generation Science Standards (NGSS) have reframed Earth science into Earth systems science, emphasizing the interacting systems of the geosphere, atmosphere, hydrosphere, and biosphere, and tying human activity and impacts to understanding each Earth system. This framing has the potential to educate students about the complex and critical issues of Earth science that most affect our lives. This is an exciting development for the Earth science education community, but one that will not be realized without deliberate efforts to reform our educational approaches.

Technology has the potential to change how students investigate geodynamic phenomena. Current technology offers unparalleled possibilities for supporting students' understanding

The geoscience projects highlighted in this newsletter all leverage current technology's capacity to develop Earth system simulations and curriculum modules to transform how Earth science is taught and learned.

of complex, invisible, and dynamic systems. Today's geodynamic simulations are transforming geology research by providing ways of understanding the processes that shape Earth's surface. Similarly, dynamic computational models with associated visualizations allow students to interact with and manipulate parameters and to observe emergent phenomena. With appropriate scaffolding, these simulations can support the development of students' understanding of complex systems and their causal mechanisms.

The *Framework* and NGSS emphasize science and engineering practices, which describe how students should engage with science ideas in ways that are epistemically authentic to the discipline of science, and include constructing evidence-based explanations of complex science phenomena. In Earth science this means students should shift from identifying and describing Earth's materials and landforms to analyzing geoscience data and constructing explanations, developing scientific arguments, and evaluating solutions. Simulations provide opportunities for discovery-based learning and offer students ways to observe and investigate systems as a whole in a manner impossible to accomplish through other avenues of inquiry. Simulations also help students to reason about some of the hidden, underlying mechanisms and physical processes and to link phenomena across scales and systems.

Simulations are thus critical to developing authentic geoscientific investigations. Computational models and simulations grounded in foundational educational research provide an ideal tool for new ways of teaching and learning geosciences. The geoscience projects highlighted in this newsletter all leverage current technology's capacity to develop Earth system simulations and curriculum modules to transform how Earth science is taught and learned.

Students use a data visualization tool and a dynamic plate tectonic model as part of the GEODE project to investigate how Earth's system of tectonic plates is responsible for geological events and has created and continues to change land formations on Earth (pages 4-5). The GEODE materials ask teachers to change how they have taught Earth science, so we have introduced an interactive teacher guide to help teachers evolve their role as facilitators and guide them on how to make sense of the technology embedded within the curriculum (pages 6-7).

The GeoHazard project introduces the variables that influence the risk and impacts of hurricanes, wildfires, and flooding on humans and how our changing climate is playing a role in the intensity of these hazards (pages 8-9). The GeoCode project (pages 10-11) is focused on engaging students in contextualized computational practices where students use block programming to code computational visualizations in order to explore hazards and risks related to a volcanic eruption. The High-Adventure Science project delves into humans' impact on Earth's systems, including climate change, the availability of fresh water, land management, and more. Kentucky high school science teacher Stephanie Harmon shares her experiences implementing one of the High-Adventure Science modules in her classroom (pages 12-13).

Each project engages students in science practices that are authentic approximations of how geoscientists undertake their work, enabling them to explore causal mechanisms, use real-world data, make predictions about real-world phenomena, and develop scientific arguments. Threaded through each project we have also been conducting research on the role of uncertainty in the study of Earth science (pages 14-15).

This special issue of *@Concord* describes our research, models, and curriculum, and what it's like to teach with this new curriculum. We are excited to share our vision for transforming geoscience education and the results of our efforts so far.

Doing Geosciences
the Way Scientists Do

By Scott McDonald

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We live on an amazingly dynamic planet. All the landforms around us—mountains, oceans, rivers, deserts, and even continents—are moving, shifting, and reconfiguring themselves in a massive ballet of rock and water. Where and how we live on the surface of our planet is determined by the interactions of Earth's plates over millions of years. Although many people think that mountains, valleys, and other landforms are static parts of our environment, these are active phenomena, though they are too large and too slow to be easily observed. It all happens at such massive scales of time and space that we see only brief snapshots of this dynamism in the form of events like earthquakes and volcanic eruptions. These invisible geoscience phenomena often significantly impact human lives.

Central to understanding geoscience phenomena, plate tectonics is the foundational paradigm and a key disciplinary core idea in the Next Generation Science Standards (NGSS) in Earth and Space Sciences. It is critical for students to understand how our Earth functions as a system of interacting tectonic plates and to understand the underlying causal mechanisms that drive that system in order to confront challenges such as managing resources, including oil, gas, metals, and sand, as well as preparing and hardening our cities to mitigate catastrophic disasters caused by earthquakes or volcanic eruptions. To address these challenges, we need to prepare students to understand plate tectonics and related disciplinary core ideas, and to reason with representations of large datasets and models that geoscientists use to investigate these astonishingly large-scale phenomena.

NGSS also emphasizes science and engineering practices. These practices (e.g., Developing and Using Models) are meant to apply to all areas of science, but the standards do not clearly articulate subtle differences between the way physicists, chemists, biologists, and geoscientists do their work. Because there is only one Earth and we cannot run experiments with it, geosciences are more observational and historical. Geoscientists examine phenomena by representing large observational datasets (e.g., earthquake epicenters) and by creating models that can be used to test assumptions and explanations against these datasets. Although one may not typically consider such activities as laboratory experiences in school science, they are indeed the epistemically authentic practices of the geosciences that students need to engage in if they are to understand how we know what we know about Earth and the mechanisms that explain how Earth works.

Earth system understanding

Research on learning progressions about plate tectonics informs us that not only do students struggle to develop system understandings of Earth, they also develop misunderstandings about both plate motion as well as the causes of plate motion based on typical approaches to teaching.[1] To address these findings, we have designed two computational models that can help students engage with geoscience phenomena in ways that are more authentic to a geoscientist's investigatory practices.

The Geological Models for Explorations of Dynamic Earth (GEODE) project has developed Seismic Explorer and Tectonic Explorer, along with a related web-based curriculum around them, which support students in developing their own explanations about the dynamic plate system on Earth. Students investigate patterns of topography and the patterns of earthquakes and volcanic eruptions around Earth and develop hypotheses regarding movement along plate boundaries that might explain these and other phenomena.

Seismic Explorer is a visualization designed to help students investigate patterns in real-world earthquake and volcanic data across the surface of Earth (Figure 1). Incorporating real-time data from the U.S. Geological Survey, Seismic Explorer displays earthquake locations, magnitude, and depth using dots of different size and color. From this data, students can see lines of earthquakes that define plate boundaries and examine how these patterns of earthquakes relate to continents and other surface features like mountains. Additionally, students can overlay volcanic data from the Smithsonian Institution Global Volcanism Program to see how earthquakes and volcanic eruption patterns occur in the same areas on Earth's surface, providing more evidence for plate boundaries. With Seismic Explorer's three-dimensional cross-section tool students can examine patterns of earthquakes beneath the surface of any place on Earth (Figure 2). They can also ask questions about the differences between subduction and divergence of plates, and the kinds of characteristic features and events that each of these boundaries produce. The goal of Seismic Explorer is to allow students to develop claims about patterns they see in large geological datasets and to propose initial explanations of these patterns.

Tectonic Explorer is a simulation of an Earth-like planet designed to provide students with a model of a dynamic plate system

Figure 1. Earthquakes visualized in Seismic Explorer. The color of the circles represents depth; the size represents magnitude.

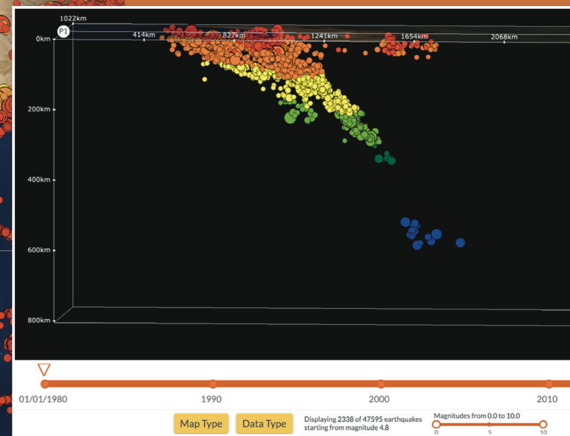

Figure 2. A cross-section in Seismic Explorer along the convergent boundary along South America. The earthquake pattern follows the descending plate.

for testing the hypotheses they developed in Seismic Explorer. With Tectonic Explorer students can design the simulation with different numbers of plates, draw continents on different parts of the surface, set the direction of plate movement with force vectors, and determine the relative density of plates, which affects which plate subducts at a boundary (Figure 3). They can run the simulation multiple times to test different aspects of the model's output. For example, they can examine in detail the model of an oceanic plate as it is subducted beneath a continental plate and forms mountains, as well as see how volcanoes form inland from the boundary. A cross-section tool allows students to see what is happening below the surface at the boundaries where plates interact.

Tectonic Explorer and Seismic Explorer are embedded into a curriculum built around explaining the phenomenon of plate

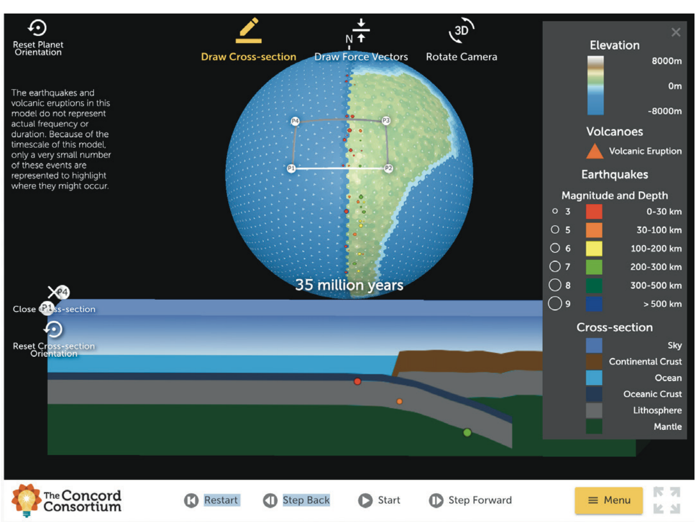

Figure 3. A model of a convergent boundary like the one along South America on an Earth-like planet. The planet view and the cross-section view in Tectonic Explorer both show earthquake and volcanic eruption representations that connect with the Seismic Explorer representations.

motion represented by GPS data and the historic model of the movement of continents. Students engage in a series of exploratory case studies of different parts of the globe that represent key boundary types and how they create specific features and events. They examine their thinking about the origin of the patterns in data from Seismic Explorer, then use Tectonic Explorer to help them understand the complex phenomena associated with plate tectonics. Using a claims, evidence, and reasoning framework, as well as asking students to think about the inherent uncertainty of the models and their claims, the curriculum creates an investigatory context for geoscience phenomena that represents a novel approach to teaching plate tectonics.

GEODE is exemplary of an approach to geoscience learning that not only helps students develop understandings of the foundational big idea of plate tectonics, but also helps them experience Earth and space science as an investigatory science. The design was informed by ambitious science teaching practices to help students develop initial explanations.[2] By giving students a context that is an epistemically authentic approximation of geoscience practices to understand large-scale and systems-level phenomena, GEODE helps students learn geoscience content and practices and expands their notions of what science practices look like.

1. McDonald, S., Bateman, K., Gall, H., Tanis-Ozcelik, A., Webb, A., & Furman, T. (2019). Mapping the increasing sophistication of students' understandings of plate tectonics: A learning progressions approach. *Journal of Geoscience Education*, *67*(1), 83–96.

2. Windschitl, M., Thompson, J. J., & Braaten, M. L. (2018). *Ambitious science teaching.* Cambridge, MA: Harvard Education Press.

LINKS

GEODE
concord.org/geode

Seismic Shifts in Supporting Teachers in **Earth Science Classrooms**

By Trudi Lord

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Plate tectonics in secondary school is rarely treated as an investigatory science as it does not lend itself well to laboratory experiments—students cannot wait millions of years for the results of an experiment. Changing how Earth systems thinking is taught is going to take a seismic shift.

To address this challenge, our GEODE project developed an inquiry-based systems approach to plate tectonics around the driving question: "What will Earth look like in 500 million years?" This plate tectonics module represents a fundamentally new way to teach the topic, turning geosciences on its head. In the curriculum module, students use our new Tectonic Explorer and Seismic Explorer models to understand that Earth's surface is a dynamic system in constant motion and to discover the causal mechanism responsible for the landforms and geologic events found on Earth.

But the module can't do it all. The teacher plays an important role as a facilitator, helping students evolve their understanding by guiding discussions, eliciting new ideas, and making sense of the multiple representations provided within the curriculum. Supporting teachers is essential as they make this shift in how plate tectonics is taught.

Summer teacher workshops have been the cornerstone of our professional development strategy for years. Dedicated teachers have met with us for days to learn about our research projects, dive deeply into both science content and pedagogy, explore our dynamic models, and learn how to teach with an online curriculum. We love meeting with enthusiastic teachers and developing a shared camaraderie, but face-to-face workshops include only a small number of teachers. Transforming Earth science education requires ambitious goals: we want to reach many more Earth science teachers so that we can explain the background and theory that led to the development of our innovative models and curriculum, share the pedagogies that work in real classrooms, and provide practical teaching tips, extensions, and other tools for success.

We set out to do that by developing the next generation of freely available just-in-time online teacher support materials that can be used as teachers both prepare for and implement the plate tectonics curriculum in their classrooms. This interactive online teacher guide was designed as part of the GEODE project.

Scaffolded interactive materials

Rather than offering a curriculum module for students and a separate teacher guide or online course for teachers, we have integrated educational materials for teachers directly into the student materials. We designed and developed an interactive Teacher Edition, where teachers learn both how to use the module and how to teach with it—in the same context as their students. The Teacher Edition adds a layer of background information and teacher tips on top of the Tectonic Explorer and Seismic Explorer models, case studies, and real-world data presented to students. The Teacher Edition allows teachers to use the curriculum wearing both student and teacher hats at the same time. We have observed in face-to-face workshops that giving teachers ample time to use the module and explore the models helped them feel comfortable, confident, and prepared to use the curriculum in their classroom.

Unique curriculum design

The Teacher Edition also gives teachers insight into the decisions we made in developing the Tectonic Explorer and Seismic Explorer models, as well as the overall curriculum. The plate tectonics module was carefully choreographed to reveal important concepts organically over the course of a five-activity sequence. The activities are designed around real-world case studies of convergent, divergent, and transform boundaries. Students look at distinctive landforms such as the Andes Mountains, the Aleutian Islands, and the Himalayas by analyzing geographic profiles and associated earthquake and volcano data. Students work with parallel representations across visualizations, including three-dimensional cross-section views, to help anchor their thinking.

Teachers are integral to helping students make connections between the models and real-world data, supporting them as they work like geoscientists, applying what they have learned about Earth's plate system to puzzle out different case studies on Earth. Drawing upon what they already learned about how Earth system processes created and continue to shape the landforms on Earth's surface, students are able to use real-world plate motion data to make predictions about what Earth might look like in the future.

Supporting model use

Seismic Explorer and Tectonic Explorer make the invisible visible. Because these models are complex and take a systems thinking approach, teacher training on how to assist students in their use is critical. The Teacher Edition provides background and tips on how to use these models, enabling teachers to guide their students in

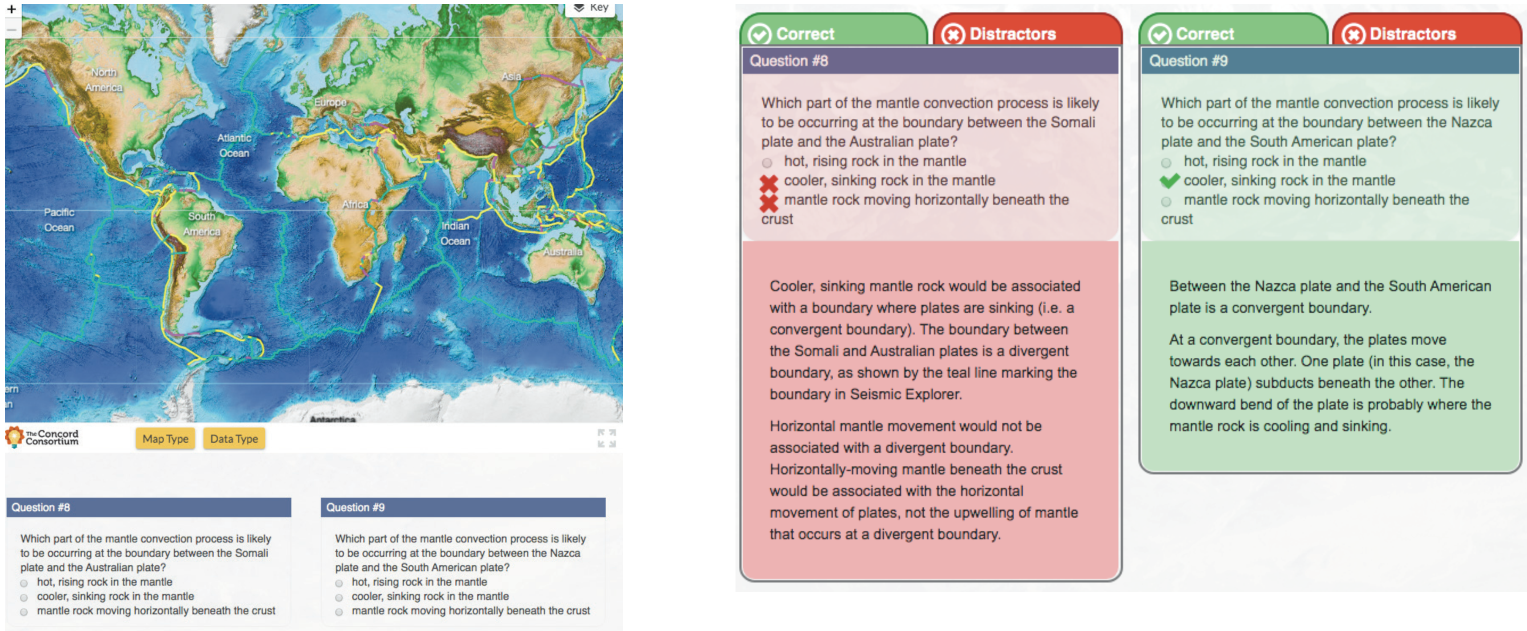

Figure 1. Student view of the model and two multiple-choice questions (left). Teacher view of the same questions with explanations of both the correct and distractor responses (right).

experimentation and construction of evidence-based explanations of phenomena. We include how-to videos on specific model features (e.g., how to create force vectors on individual plates in Tectonic Explorer), as well as pedagogical strategies on how to best engage students in using and making sense of multiple representations. When new parts of Seismic Explorer and Tectonic Explorer are introduced, we explain many of the design decisions that went into that model, what variables we left in, what we left out, and why.

Evolving student understanding

An important feature of the Teacher Edition focuses on giving teachers insight into student responses to the questions embedded in the plate tectonics module. Using the Teacher Edition, teachers can answer the questions just like their students. The Teacher Edition also offers exemplar answers to free response questions and explanations of multiple-choice questions covering both correct answers and distractors (Figures 1 and 2). Using our knowledge of learning progressions and student misconceptions, we are able to help teachers interpret student responses, detect misunderstandings, and offer suggestions. Teachers can look for evidence of student understanding in their written responses. We also encourage student discourse and strategically place discussion prompts at specific points in the curriculum, giving teachers pre-determined places to stop the class and engage students in either whole-class or smaller group discussions.

Extending the curriculum

Throughout the plate tectonics module, case studies and real-world data help scaffold and extend the curriculum. Each of these elements, including data tables, charts, videos, and graphics, are enhanced with tips for teachers that provide instructional resources and methods that teachers may find useful as they help their students achieve the learning goals. The Teacher Edition also provides extension resources for students who are ready to dig deeper into the material. Each tip type includes text explanations, images, and videos, as well as links to primary source data.

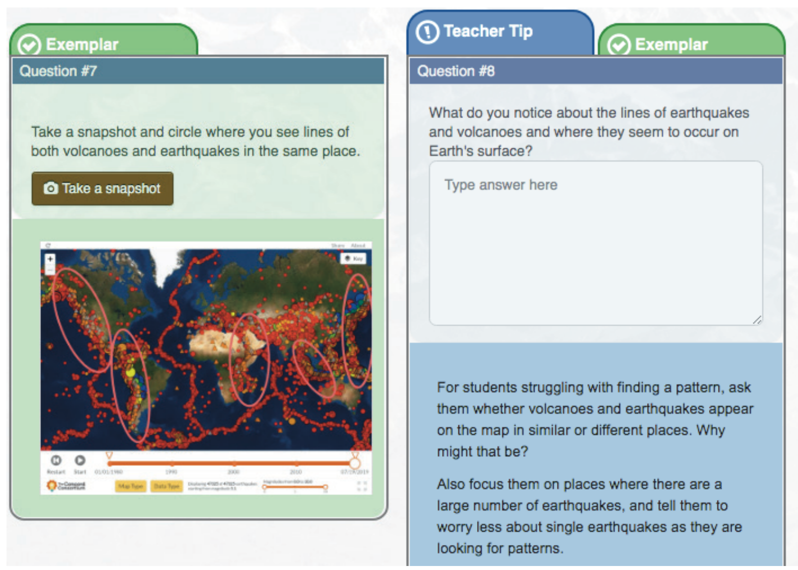

Figure 2. Teachers have access to question-specific tips as well as exemplar student answers.

What's next?

The goal of the Teacher Edition is to explain our approach to inquiry-based learning and make our intentions for the design and use of the models and curriculum explicit. We hope that by using these resources and scaffolds, teachers will be able to help their students reach a more robust level of understanding of complex Earth systems. To encourage the essential shift in Earth science education, we are developing Teacher Editions for additional curriculum modules in our GeoHazard and GeoCode projects, so more teachers and students experience Earth science as an exciting lab-based science where investigation and sensemaking are critical for understanding the complex Earth we live on.

LINKS

GEODE
concord.org/geode

Exploring the Spread of Wildfires

and Interpreting Their Risks

By Chris Lore

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Turn on the news and you will likely hear about a natural hazard. Wildfires in California, flooding in the Midwest, hurricanes across the Atlantic Coast. Natural phenomena cause widespread damage and destruction, and lately they seem to be more frequent and severe. Faced with an imminent threat, however, there is precious little time to research occurrence or risk factors, or to develop a comprehensive plan of action. Indeed, there may be only days or even hours to make a decision: stay or evacuate? A more informed public with a better understanding of the science behind natural hazards can more effectively interpret the risks associated with the hazards and consider vulnerabilities that were previously overlooked.

The goal of the GeoHazard: Modeling Natural Hazards and Assessing Risks project is to integrate Earth systems models with easy-to-use data analysis tools. These tools allow students to evaluate natural hazards holistically, including the factors that influence their formation, progression, and severity, and that contribute the most to potential risks. The project focuses on three common natural hazards: hurricanes, wildfires, and floods.

Similar to geoscientists who have harnessed the power of new technologies to look at natural processes in unique ways, GeoHazard uses computer simulations to address these natural hazards in science classrooms. Earth is a set of complex systems and it is critical to observe the interactions among the subsystems.

Modeling of natural hazards like floods, wildfires, and hurricanes has advanced over the last 30 years, and geoscientists now have the ability to accurately predict the propagation and impacts of each hazard in thousands of different virtual scenarios. Every time a natural hazard occurs, scientists update and refine their models by including this new data. As models recalibrate with the new information, scientists gain a better understanding of the phenomena under study. By constantly collecting data and improving computational models, scientists not only understand the phenomenon better as a whole, but can also define the influence of each variable in the system more accurately. A critical development in the study of most natural hazards is that we now understand the system variables so well, it is no longer necessary to go into the field and observe them for ourselves in order to learn more. Instead, we can safely conduct experiments under different scenarios from the comfort of a computer lab. The study of natural hazards has shifted from a slow, dangerous, purely observational science to an efficient, safe, and investigative one.

Using sophisticated modeling technology, students also have the ability to examine causal mechanisms and investigate multiple factors simultaneously. Importantly, they can experiment with Earth systems in a holistic way in order to fully understand emergent properties like natural hazards and their effects on humans.

Wildfire Explorer

The GeoHazard project has developed a curriculum module and a simulation to help students investigate wildfires. When used together, they help form and elicit student ideas about the risks and hazards wildfires pose to people and communities in their path. Additionally, the scientific factors that affect the formation, propagation, and intensity of wildfires are used to explain when and why wildfires turn from a natural phenomenon to a natural hazard.

Wildfire Explorer merges calculations of wildfire spread with visualizations of fire expanding over landscapes similar to those in the Midwest and western United States. The equation used to calculate the behavior of a fire was developed by the U.S. Geological Survey and has been used for fire and vegetation management since 1972. Rothermel's equation, as it is called, considers both environmental parameters such as wind speed, wind direction, and topography, as well as vegetation characteristics like size, depth, density, and volume. Students can experiment with five variables in the model to understand their effect on wildfire spread: terrain, drought levels, vegetation type, wind speed, and wind direction.

The visualization of Rothermel's equation is a zoned landscape comprised of mountains, hills, or plains. Through the Terrain Setup window (Figure 1), students set values for each variable. The visualization updates as each parameter is set, showing unique colors for different drought levels, a compass rose depicting wind speed and direction, and other features such as towns and rivers. Finally, students place one or more sparks on the model to simulate an ignition point. As the fire spreads, the model displays the emergent behavior of wildfires. For example, students watch as fire shoots up the side of a mountain and at the same

Figure 1. In the Terrain Setup window, students change input parameters of the Wildfire Explorer model to observe how each variable influences wildfire spread.

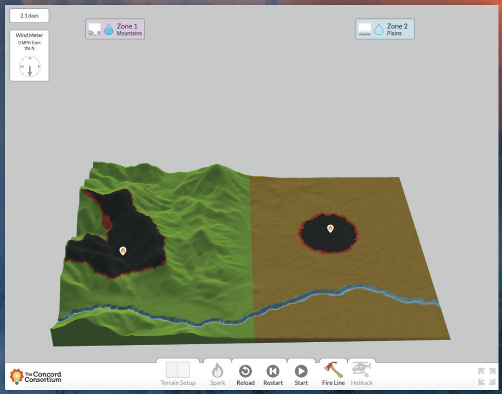

Figure 2. Wildfire Explorer includes a visualization of fire spread over time (the dark, charred areas in the mountains and plains), allowing students to observe emergent properties of wildfire behavior.

NATIONAL GEOGRAPHIC

Photo credit:
Michael Melford
National Geographic
Creative

Figure 3. A wildfire burns ferociously in Glacier National Park in 2007.

time see another fire progress evenly across a plain (Figure 2). This simultaneous, side-by-side comparison allows students to observe change over time and is essential to understanding how each variable influences spread.

In addition to learning about different factors that affect wildfire spread, questions in the curriculum prompt students to use what they know about spread to grapple with questions about risk and impacts. Risk assessment involves judging both the likely occurrence of an event and the likely damage caused by the event. In the case of natural hazards, not all people and locations are impacted in the same way. Is a town in the mountains in greater danger of wildfires than an apartment in the city? If a community is built around a river, does that mean it is impervious to burning?

Wildfire Explorer includes two types of fire fighting techniques, firelines and helitacks. Firelines are built by teams of firefighters in the real world and are simulated in the model by drawing a line across the land in an attempt to contain fire spread. Helitacks are used to douse swaths of vegetation by helicopter in the hope of making it too wet to burn. As the wildfire spreads in the model, students have to make quick decisions to understand which areas are the most at risk, and, therefore, where to use available resources to slow the fire down or protect those regions.

Finally, students use the model to answer the framing question of the curriculum: "How will wildfires change in the next 100 years?" Global climate change is altering everything from ecosystems to weather patterns, and wildfire behavior is influenced heavily by these changes. Using the model, students can represent both increased drought and changing vegetation caused by climate change. They are prompted to experiment with the ways these shifts affect the risks of wildfires. They are also encouraged to examine how mitigation efforts have to change in response to stronger or bigger fires, and to consider deeper, long-term changes society can make to reduce the risk of wildfire hazards.

As the adage goes, knowledge is power. The GeoHazard project aims to help students understand natural hazards as they develop scientific reasoning in the context of risk. In a world of increasingly frequent natural hazards, informed action is the best way to mitigate disasters.

LINKS

GeoHazard
concord.org/geohazard

Visualizing Geohazards and Risk with Code

By Noah Paessel

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When the 1992 Cerro Negro volcano in Nicaragua erupted, it released billions of kilograms of tephra—fine particles of ejected rock—over the course of two days. People living near the volcano were affected by this mighty display of power. The tephra and magma that were ejected by the volcano damaged buildings, contaminated water supplies, destroyed plants, hurt animals, and caused human health hazards. Despite widespread damage, the Cerro Negro volcano is considered a fairly small eruption. In more recent years, much larger volcanic eruptions in Alaska and Iceland have disrupted aviation and posed health risks for people living even farther from the volcanic sources. In December 2019, the volcanic island of Whakaari in New Zealand erupted, killing 19 tourists, reminding us that even small eruptions can have fatal consequences.

To understand such potential risks, scientists who study active volcanoes like Cerro Negro look at factors that influence how tephra travels and where it may land. They dig pits in past eruption locations to discover the volume and distribution of tephra and draw maps of where the tephra fell. Geoscientists use these observations of past eruptions to create models, using them to predict the impacts of future explosions. By understanding the mechanisms that cause such geohazards, scientists can consider the potential impacts and dangers. Their work also helps citizens understand their community's vulnerability and exposure to imminent risk.

Data fluency in scientific practice

Our Visualizing Geohazards and Risk with Code (GeoCode) project was developed in response to the National Science Foundation's STEM+C challenge to develop computational literacy in U.S. schools. The C stands for computing, and the program recognizes that current scientific and engineering disciplines require integrated computational literacy. The goal of the GeoCode project is to help high school students understand, construct, interpret, and revise computational visualizations so they can explain scientific phenomena and make predictions about the probability of risks. Our pedagogical model combines scientific inquiry and computational thinking in a way that mirrors geoscientists' modeling of geohazards.

Students focus first and foremost on the phenomenon of volcanoes, the geologic conditions that cause them, and the risks they pose. Volcanologists at the University of South Florida have helped us frame our curriculum so that it engages students in computational practices that closely match the methods they use in their research. By introducing computation into the geology curriculum, we are giving students tools to facilitate authentic experiments that address the hazards and risks to people living near volcanoes. We expect that students will also develop an instinct for identifying problems outside of geoscience that are also amenable to computational approaches.

GeoCode Explorer

Our GeoCode Explorer programming environment challenges students to model tephra impact by applying the practices utilized by volcanologists. We use a visual block programming language called Blockly to provide a simple but robust coding workspace that doesn't overwhelm students, since the principal goal is to learn about volcanoes. We integrated Blockly into a simulation environment that includes a tephra distribution model built by our partners at the University of South Florida, and added a suite of custom blocks that provide access to data, graphs, charts, and maps (Figure 1).

Students learn about the Cerro Negro volcano by using GeoCode Explorer to isolate different variables that contribute to tephra fallout patterns. The two-week curriculum gradually introduces computational practices, such as problem decomposition, conditional expressions, and looping, while asking students to explore more complicated questions. Which towns are likely to be affected by fallout if the wind is blowing out of the east? Using historical records, how likely will the wind be blowing in that direction on any given day in October?

Initially, students manipulate sliders that change the input parameters of the simulation one at a time. For example, they observe how the wind direction impacts the amount of tephra that lands on a nearby town. Next they examine how the eruption volume impacts the neighboring communities. Throughout the activity, we introduce students to increasingly sophisticated programming blocks. Students learn about "variables" as both a scientific idea and a programming construct. Similarly, students build programs that repeat experiments while systematically changing and constraining variables. These loops and variables are a cornerstone of computer programming and ultimately speed up analysis.

Monte Carlo simulations to assess risk

Despite the hazards of volcanoes, many people live near them and know that an eruption could happen at any time. Tephra is particularly destructive and poses many risks to these communities. The job of scientists is to assess the environmental risks of future eruptions and communicate these to affected communities.

Using historical wind records and tephra distribution data from past volcanic eruptions, volcanologists can produce accurate assessments and maps by running thousands of computer simulations. This general approach is known as the Monte Carlo method, which describes a range of computational algorithms that use random data sampling to obtain probabilistic results. Input parameters are selected from an enormous set of observations—the more random samples that are drawn, the higher the confidence in the distribution of outcomes. This approach is decidedly computational because it leverages the speed and data processing capabilities that computers provide.

At the end of the GeoCode module, students produce their own risk assessment maps. Given a map with a volcano and nearby school, students should be able to answer questions such as "How likely is it that the next time this volcano erupts, the school's roof will collapse?"

One way to answer such questions is by using a simplified version of the Monte Carlo approach favored by volcanologists. The prospect of running a thousand simulations required by this approach would not usually occur to students. To consider this, they must have a computational instinct, knowing that computers can easily facilitate jobs that involve repetition and variable substitution. Can we help students build those instincts?

A 21st century literacy

While language arts and mathematics were the foundational skills of the 20th century, computational literacy is critical for the 21st century. Computers are ubiquitous in the workplace, regardless of the industry. Scientific research, in particular, will require increased facility in the use of machines and algorithms to make sense of the petabytes of available data across all scientific disciplines. Indeed, today's scientists and academics are foregrounding the computational nature of their work by publishing not only their research findings, but also the data and algorithms they used in their research via interactive lab books written in R or Python, for example.

Now more than ever, authentic inquiry-driven experiences require proficiency with data and data processing tools, as well as the computational thinking skills to construct explanations and design solutions. The GeoCode project aims to equip students with a deep awareness of computation and provide them contextualized opportunities to flex their data sleuthing muscles.

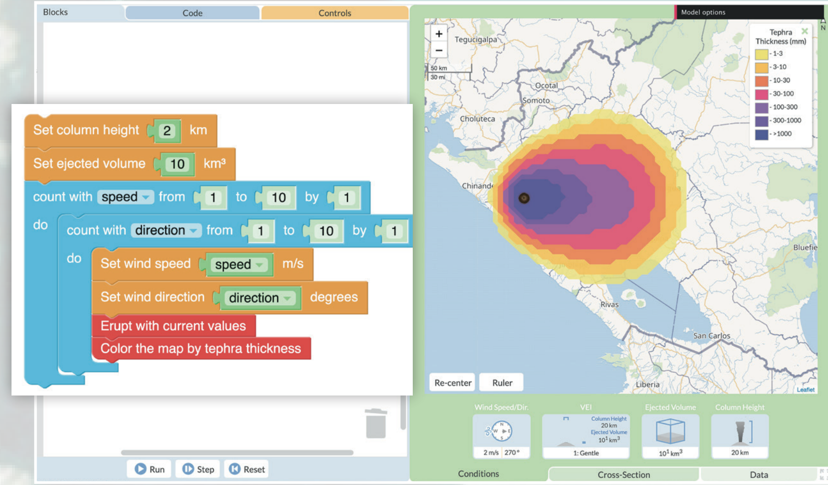

Figure 1. Using GeoCode Explorer students examine how the wind impacts tephra dispersion from Cerro Negro. The block program loops through different wind speed and wind directions (left). As it runs, it repaints the map, showing the computed tephra depth around the volcano (right).

Figure 2. Volcanic ash and hot rock fragments cascading down Mount St. Helens during the May 18, 1980, eruption.

LINKS

GeoCode
concord.org/geocode

Can We Feed a Growing Population?

Using Simulations to Engage Students

By Stephanie Harmon and Sarah Pryputniewicz

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We live in a changing and dynamic world where so much takes place outside the science classroom. Energy flows, water cycles, clouds form, and plants grow. My students want to know what's happening, especially with phenomena they can't see for themselves. For instance, when I teach about land uses in my high school Earth science class, my students are often confused that soil changes over time and is affected by human behavior. Models and simulations can help students see what's happening. So I love the High-Adventure Science module "Can we feed the growing population?" which incorporates models of land use.

We live in a rural part of Kentucky. Questions about land use are both local and real. So I start by asking my students, "Will we always be able to produce enough food to feed everyone?" I listen as they share their thinking about issues that impact local food production, including how human behavior influences land use and the quality of agricultural land. We discuss the shift in the number of acres used for agricultural purposes and how that has affected our economy.

Then we get started with the High-Adventure Science curriculum module. In the first activity, students examine plant growth, using embedded prompts to help scaffold their sense-making of the data. In the first of many "argumentation sets" throughout the module, students make a claim about the relationship between crop yield and soil potassium levels. Then they rate how certain they are about their claim based on the quality of the evidence and write an explanation of this certainty rating. This allows them to evaluate the merits of the evidence.

Before continuing with the next online activity, we spend several class periods collecting and analyzing the physical and chemical properties of the soil on our school campus, including the potassium level. Students use this data to make comparisons of their findings and the scientists' data. This real-world data collection and analysis allows students to deepen their learning, discuss findings, and reevaluate their initial arguments. Students revisit their responses in the first activity, making changes to their arguments as they gather new information. Importantly, they also learn that scientists continually use new evidence to construct and revise explanations.

Exploring different variables

When we return to the module, students examine global land use and discover how soil is formed. The computer model allows students to explore what happens to different landscapes over a period of time as they change variables and compare outcomes for two different land management zones. Students see beyond (and below) the surface as they change the slope of the landscape and note whether plants are present in each zone, and observe time-lapsed graphs of erosion rates and topsoil amounts. Such experiments are impractical or impossible in the real world, where these events are too slow to investigate firsthand or could result in potentially negative outcomes.

Using the model, students simulate several possible scenarios, such as planting vegetation on bare slopes to conserve soil, and gather data to support real-life choices. They can use the model to consider whether or not grass should be planted in a new housing development to prevent soil erosion. For example, in our area, we are witnessing an increase in local residential development and the impact on agriculture production.

Throughout the module, students explore new variables as they are added to the same model. As the complexity of the model increases, students are able to evaluate factors that are difficult to see in daily observations, such as slow erosion and farming practices and their long-term impact on soil quality. They watch as soil erosion is affected by climate factors, including precipitation levels. Students continue to answer questions in the form of argumentation sets. Using claims, evidence, and reasoning, they evaluate the evidence generated in the models to determine which land management practices are best, such as when vegetation presence is most useful and which vegetation type is best.

One of my favorite parts of the class is the full-group discussions. Students bring questions from their own lives and from the curriculum:

- How can the quality of the soil be restored if the same crop has been grown in the same location for many years?
- Does soil erosion affect our local water supply? Do these materials flow into the lake?
- What happens to topsoil that is moved from the site of a subdivision or a new home site?

Figure 1. A setup of the land model showing the effect of slope and vegetation on erosion. Grass is planted in Zone 2, while Zone 1 is left bare. Both zones are set to the same slope. The graphs show higher erosion rates and lower amounts of topsoil in Zone 1 compared to Zone 2.

Figure 2. A setup of the land model with additional variables for climate. Students choose different climate settings to get different precipitation levels throughout the year. This model also includes a measure of soil quality, so that students can see that maintaining good soil is about more than making sure it doesn't erode away.

Photo credit: U.S. Department of Agriculture

Students exchange ideas with each other in the same way that scientists do. This kind of discourse is important. It is also the epitome of the Next Generation Science Standards (NGSS) practice of Obtaining, Evaluating, and Communicating Information.

Monitoring student progress and learning

To assess student understanding, I use the pre-test and post-test included with the module. Rubrics for explanations and certainty ratings allow my students to self-assess and assist me in providing feedback. Other embedded tools allow me to monitor student progress and learning. I can check individual student performance and whole-class progress at a glance using the Teacher Dashboard to access students' responses to embedded questions and their saved models. Individual student reports allow me to check student understanding while reports on specific questions allow me to determine where the entire class is in their thinking. This enables me to identify misconceptions, ask clarifying questions, and determine what my students need to support their understanding.

The Teacher Portal also allows me to provide student feedback. Students access the feedback when they log into the module, and use it to examine their thinking and revisit portions of the curriculum. They edit their responses as new learning occurs. As students complete the module, I compare their pre- and post-test responses to determine their level of understanding.

Conclusion

"Can we feed the growing population?" helps students understand the human impacts on food production. But it does so much more. Students run simulations, examine evidence, and discuss their findings with each other—in the same way that scientists and researchers do—while engaging in many of the NGSS science and engineering practices, especially Developing and Using Models and Engaging in Argument from Evidence. Students evaluate the strengths and limitations of models, predict relationships between components of a system, and make and defend claims based on evidence about the natural world.

I've been teaching with High-Adventure Science for seven years. These curriculum modules have helped my students understand the value of scientific modeling and become more capable in constructing scientific arguments, giving them the tools to answer questions about the world around them.

LINKS

High-Adventure Science
learn.concord.org/has

Making Uncertainty Accessible

By Hee-Sun Lee

Theoretical physicist Werner Heisenberg once proclaimed, "What we observe is not nature itself, but nature exposed to our method of questioning." The goal of science is to develop a fundamental understanding of natural phenomena, but the road to understanding is neither straightforward nor simple. Nature is complex, and it is this complexity that both excites scientists and limits their explanations.

Uncertainty cannot be avoided in scientific research. Indeed, it is an essential part of doing science. Uncertainty comes from limitations in theories and methods applied by scientists, including what they know already, what instruments they use to collect data, how they sample data, and what analyses they use to uncover mechanisms among identified variables. Recognizing uncertainty in science means understanding how scientific knowledge develops over time. Uncertainty invites productive, critical reflections on what can and cannot be explained. And it requires minimizing known errors and making room for the potentially unknown.

However, uncertainty is rarely introduced in science classrooms for the fear of making students science doubters. For example, *A Framework for K-12 Science Education* seems to recommend avoiding the discussion of uncertainty in science: "although science involves many areas of uncertainty as knowledge is developed, there are now many aspects of scientific knowledge that are so well established as to be unquestioned foundations of the culture and its technologies."[1] Nonetheless, over the past decade we have made important research contributions on the role and nature of uncertainty. And the overarching goal of the National Science Foundation-funded projects featured in this issue is research on the role of uncertainty in the study of Earth science.

Eliciting uncertainty in scientific argumentation

To elicit student ideas about uncertainty, we created uncertainty-infused scientific argument writing tasks in the High-Adventure Science modules. After students investigated data from scientists or from computational models, they were asked to make a claim, explain their reasoning based on data to justify the claim, select their level of uncertainty from 1 (not at all certain) to 5 (very certain), and attribute sources of uncertainty. We validated these scientific argumentation tasks along with the rubrics.[2] The analysis of pre- and post-tests of roughly 6,300 students taught by 132 teachers showed significant improvements in writing scientific arguments with uncertainty after they completed the modules (from 0.35 to 0.54 standard deviations).

Characterizing a taxonomy of student uncertainty attribution

Based on our analysis of students' uncertainty-infused scientific arguments, we constructed a taxonomy representing five distinct ways students attribute sources of uncertainty:

1) Students include no information about uncertainty attribution.
2) Students express personal uncertainty attribution statements.
3) Students use words like "data," "reasoning," or "knowledge" without citing any specific details.
4) Students include scientific descriptions of the theoretical basis or empirical findings associated with the investigation.
5) Students elaborate theoretical, empirical, measurement-related, and analytical limitations associated with the investigation.

This taxonomy can be used by teachers to engage students in productive discourse about the scientific uncertainty involved in their investigations and about the nature of science.

Supporting uncertainty attribution through automated feedback

After years of honing and validating the scientific argumentation tasks and rubrics, we developed automated scoring models to evaluate students' performances and to identify types of feedback students would need to improve their performance. We engineered an automated scoring and feedback system called HASBot and embedded it within the uncertainty-infused scientific argumentation tasks in two curriculum modules on climate change and water sustainability. Students submitted their initial scientific arguments and received an automated score and feedback in real time with HASBot. Eighteen teachers from 11 states implemented the two modules. Our findings show that students wrote significantly better scientific arguments after the climate change module (a 0.85 standard devia-

to Science Students

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tion increase) and the water sustainability module (a 1.52 standard deviation increase).[3]

Examining uncertainty arising from simulation models

We are currently exploring different ways to support students' consideration of uncertainty and elicit their thinking about it. In the GEODE project, for example, students make model-based claims to explain real-world evidence in the context of plate tectonics. They are scaffolded to examine the limitations in applying knowledge gained from Tectonic Explorer models to the real-world seismic and eruption data visualized in Seismic Explorer. We are investigating how students address sources of uncertainty while connecting model-based understanding to real-world data.

Characterizing risks associated with natural hazards based on uncertainty

A new area of research includes the study of natural hazards, which allows us to explore uncertainty involved in risk assessment. In order to make predictions, scientists identify patterns from historical data and interpret them based on their understanding of how natural phenomena, such as hurricanes and wildfires, behave. Four types of uncertainty operate while considering hazards and potential risks: 1) measurement uncertainty in data collection, 2) modeling uncertainty of complex systems, 3) temporal uncertainty due to difficulties in recounting past events and predicting future events, and 4) transitional uncertainty in sensemaking and communicating about uncertain results. We are exploring how students think about and practice uncertainty during their investigations of risks, in particular on system uncertainty (i.e., complex systems cannot be modeled exactly) and prediction uncertainty (i.e., future events cannot be predicted precisely).

Estimating uncertainty through Monte Carlo simulation

We are also exploring how students make sense of risk when it's represented as the probability of experiencing a negative impact due to a natural hazard for a given location. Students learn how volcanologists estimate the probabilities of hazardous events (e.g., the collapse of a building), and they are guided to program computational models to represent variables and their relationships. For instance, students model how tephra disperses after volcanic eruptions. Like scientists, students estimate the risk for a particular negative impact to a community living near a volcano. We are currently exploring how students interpret the uncertainty as represented in the output of a Monte Carlo simulation.

Our research on uncertainty has evolved. Each new project brings its own challenges in designing curriculum and assessment materials so students can think about the uncertainty embedded in science. Throughout, we hope to teach students how to weigh evidence, what it means when an Earth scientist talks about uncertainty in data, how models are critical tools for understanding Earth phenomena even though there are limitations to using them as evidence for scientific claims, and how estimating probabilities of risk and impacts is critical even in the face of uncertainty. We hope that students learn that science includes both curiosity and uncertainty, and that it is possible to refine our understanding of the natural world while at the same time embracing uncertainty as an important feature of the scientific endeavor.

1. National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*, p. 44. Washington, DC: National Academies Press.

2. Lee, H.-S., Liu, O. L., Pallant, A., Roohr, K. C., Pryputniewicz, S., & Buck, Z. E. (2014). Assessment of uncertainty-infused scientific argumentation. *Journal of Research in Science Teaching*, *51*(5), 581-605.

3. Lee, H.-S., Pallant, A., Pryputniewicz, S., Lord, T., Mulholland, M., & Liu, O. L. (2019). Automated text scoring and real-time adjustable feedback: Supporting revision of scientific arguments involving uncertainty. *Science Education*, *103*(3), 590-622.

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Free Classroom Resources

Many of the innovative classroom and teacher resources described throughout this Earth science special issue are available for free. Others will be available over the coming year. Designed for middle and high school students, the online curriculum modules include one or more Earth systems models plus pre- and post-assessments and are aligned with the Next Generation Science Standards disciplinary core ideas in Earth and Space Sciences, science practices, and crosscutting concepts. Join a large (almost 500,000 users) and growing community from all 50 states and across the globe by registering on the Concord Consortium's STEM Resource Finder. You'll get access to these resources and more, plus Teacher Editions with detailed background information, tips, and exemplar student responses, as well as classroom management tools, reports, and a real-time dashboard to help you keep track of student progress.
learn.concord.org/earth

Publications for Teachers and Researchers

For ten years we have researched how Earth systems models and innovative technologies are transforming the way Earth science is taught and the way students learn. We have made significant contributions to the science education and research communities with 25 articles for teachers and researchers focused on modeling, uncertainty-infused scientific argumentation practices, and real-time automated feedback. We describe how to address sources of uncertainty as well as how we structured tasks, validated items, and measured students' scientific arguments. We explore the instructional dilemmas teachers face when including Earth systems models as part of their curriculum, and the potential scaffolding necessary to shift how teaching and learning occur in classroom settings. We consider how students use models as evidence when constructing scientific arguments and study how a computerized formative assessment system that provides automated scoring and feedback can help students write more sophisticated scientific arguments.
concord.org/publications/earth

Get Notified

New models, curriculum units, and teacher resources on hurricanes, wildfires, and volcanoes will be available starting in summer 2020. Sign up now to receive updates when new resources are released, or when opportunities to participate in current or future research projects arise.
surveymonkey.com/r/cc-earth

Amazing Partners

Through our many National Science Foundation-funded projects described in this special issue, we have had opportunities to work with amazing partners, including National Geographic Society, Pennsylvania State University, University of South Florida, Educational Testing Service, University of California, Santa Cruz, TERC, and UNAVCO. We also thank the incredible teachers who have attended our workshops, pilot tested our resources, and provided invaluable feedback.

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