GeoHazard: Modeling Natural Hazards and Assessing Risks

"Unfortunately, we can't prevent natural disasters or predict them with 100 percent certainty," states Professor Felix Riede, "but we can find out whether we can make our societies more resilient to natural disaster." [1]

Importance

From severe flooding to sustained winds of hurricanes to powerful earthquakes and unstoppable wildfires, natural disasters around the globe have caused devastation and had major impact on millions of people's lives. What do scientists understand about such extreme events? How can understanding natural hazards help people plan for and recover more quickly from these impending threats?

Understanding natural hazards is among the most relevant challenges of our age. With the news cycle relentlessly detailing how natural hazards impact our lives, there is a critical need for innovative Earth science educational materials that help students interpret data and understand the factors influencing the progression of and the risk associated with natural hazards. The content involved in understanding natural hazards should be based on core Earth systems concepts allowing students to consider factors that influence changes in system behaviors and associated risks. Though the instinct is to teach about natural hazards when there is peak interest in response to current events, these topics also provide a hook for thinking about complex systems in general. Hundreds of millions of people around the world live in areas prone to natural hazards. Studying the processes underlying them, as well as the relationship between humans and the environment, could enrich Earth science curricula and provide learners with valuable insights into the impact of extreme natural events on mankind.

Understanding natural hazards demands an understanding of complex systems. Like most geoscience topics, teaching about natural hazards poses interesting challenges. Natural hazards are the result of the interactions of many factors in a system. Scientists have relied on modeling as a way to explore such systems [2]. Computer-based modeling provides learners and scientists alike with visual and interactive experimentation of a system [3]. Science education has recognized the importance of dynamic models when teaching about complex systems, because they afford users the ability to visualize and manipulate the whole system as well as the parts of the system simultaneously, an ability that is often not afforded in the real world [4].

Teaching about natural hazards means teaching both the science and the concept of risk. The study of natural hazards, however, is not solely about the underlying core science; it also requires people to be able to assess risk, which involves judging both the likely occurrence of an event and the likely damage caused by the event [5]. The *Next Generation Science Standards* (NGSS) advocates for the inclusion of natural hazards content in Earth science classes in both middle school and high school. Specifically, NGSS suggests that students should analyze and interpret data on natural hazards, consider technologies to mitigate their effects, and use evidence to build scientific arguments about how they have affected human activity. Despite the call for integrating the science concepts with the impact on humans, natural hazards are not often emphasized in Earth science curricula. Textbooks typically reference extreme weather or earthquake disasters as sidebars or case studies. There are a wide range of web-based videos and online activities that highlight aspects of a given natural hazard. Yet the richness of these topics requires an instructional method and materials that are able to scaffold the development of profound content knowledge and the exploration of large amounts of data. Learning about natural hazards with Geographic Information Systems (GIS) has the potential for students to investigate these phenomena by analyzing data and using spatial visualizations [6]. Many of these GIS curricula are excellent, but we have an opportunity to develop new ways to connect current Earth systems models to data exploration tools in a way that could accelerate students' development of conceptual models.

The time is right to develop active, technology-enabled systems and data modeling approaches to natural hazard pedagogy. Current state of the art technology that can be used for learning sciences make this an ideal time for new instructional approaches. The design and development of curriculum materials that integrate Earth systems models along with an easy-to-use data analysis tool will allow students to make sense of the fundamental science concepts and enable them to evaluate natural hazards holistically: what causes them, the factors that influence the formation, progression, and severity of the hazard, and which factors contribute most to potential risks. The GeoHazard project takes full advantage of this opportunity. Students will experiment with Earth system models and real-world data and use evidence from their exploration of both, to develop scientific arguments focused on risk analysis and level of uncertainty related to risk. This holistic approach will allow students to simulate a wide variety of possible scenarios and engage in authentic scientific practices, exploring the limitations and uncertainties of these models and the predictability of outcomes as they compare outcomes to real-world scenarios.

GOALS AND OBJECTIVES

The Concord Consortium (CC), in partnership with Pennsylvania State University (PSU), National Geographic Society (NGS), and TERC proposes a four-year Early Stage Design and Development proposal addressing Strand 2, Learning. The goal of GeoHazard is to design Earth systems models and curricula to help students understand the processes underlying natural hazards and extreme events, explore the predictability of the events, as well as their physical impacts, and how each hazard coincides with human vulnerability. Students will then consider risk—specifically the likelihood of potential loss for humans by impending and future hazards and ways in which people are monitoring hazards and mitigating risks.

Objective 1: Develop interactive curriculum materials. The GeoHazard project will create middle and high school technologically enhanced curricular materials that feature computational models and data analysis tools for four extreme event types: hurricanes, flooding, wildfires, and earthquakes. Each curriculum module will require the development of a set of Earth systems computational models designed specifically to explore geoscience systems responsible for the natural hazard and the modification of an open-source data analysis tool to visualize the magnitude and frequency of real-world hazards and the impact of hazards on people in order to predict the likelihood of future impacts.

Objective 2: Conduct targeted research on teaching and learning. Research will focus on curricular modules and assessment materials. Modules will be developed through three cycles of design-based research. In the first design cycle, the GeoHazard models will be tested with scientists, students, and teachers in think-aloud settings. In the second design cycle, research will be conducted on a prototype of each module. In the third design cycle, revised curricular modules will be tested with five lead teachers in diverse school settings. In the final phase of the project, we will test the curricular modules with a larger number of teachers in diverse classroom settings. Targeted assessments and teacher professional development and learning will be researched and continually revised throughout the project.

Objective 3: Disseminate broadly. We will produce revised and polished materials ready to be promoted and distributed *for free* to a national audience through web resources on the National Geographic Society Education website and on the Concord Consortium website, as well as through a partnership with the National Earth Science Teachers Association (NESTA) network and share-a-thons. We will publish research results in peer-reviewed journals for teachers as well as for researchers and developers in science education and learning sciences. We will also present at conferences and disseminate curricula and assessment materials through teacher networks.

Results from prior NSF support

The **High-Adventure Science (HAS)** and **High-Adventure Science: Earth's Systems and Sustainability (HAS: ESS)** projects *(PI: Pallant with Co-PIs Lee and Larson; DRL-0929774; $695,075; 9/15/09 – 8/31/12; DRL-1220756; $2,328,593; 10/1/12 – 12/31/16)*. ***Summary of project results.*** This pair of HAS projects developed six modules for Earth and environmental science classes in order to test the hypothesis that students who use computational models of complex Earth systems (Figure 1), analyze real-world data, and engage in scientific reasoning and argumentation practices will be better able to understand core ideas about Earth systems science and the impact humans can have on these systems. Analysis of pre- and post-tests administered before and after each HAS module showed significant improvement in student argumentation and systems dynamics thinking across diverse school settings—these modules improved student argumentation by effect sizes (Cohen's d) ranging from 0.35 to 0.54.

Intellectual merit: These projects have manifested four design principles to address how to incorporate scientists' current empirical research and modeling practices into short duration, inquiry-based curriculum modules. These projects have created and validated two separate assessment frameworks: uncertainty-infused scientific argumentation and system dynamics thinking related to Earth systems. ***Broader impacts:*** The HAS modules have been distributed widely *for free* through the National Geographic Society and Concord Consortium websites. As of today, 132 teachers and roughly 6,300 students have participated in field testing of the modules as part of the HAS and HAS: ESS projects. In addition, Google Analytics shows 210,000 visitors to the HAS website in 2017, producing a large and growing independent community of registered users (67,000 registered users) across all 50 states. ***Publications:*** This work has been extensively documented in six peer-reviewed research publications for assessing students' uncertainty-infused scientific arguments [7]; analyzing student articulation of uncertainty in argumentation [8], specifying a methodology for promoting scientific argumentation using computational models [9], a method for using stocks and flows as a framework to structure students' exploration of models and thinking about sustainability [10], and instructional dilemmas and opportunities provided by the use of digital curricula [11]. In addition, six peer-reviewed papers were published in teacher journals [12]–[17]; three in-house newsletter articles were published [18]–[20]; and 11 conference presentations were made [21]–[30].

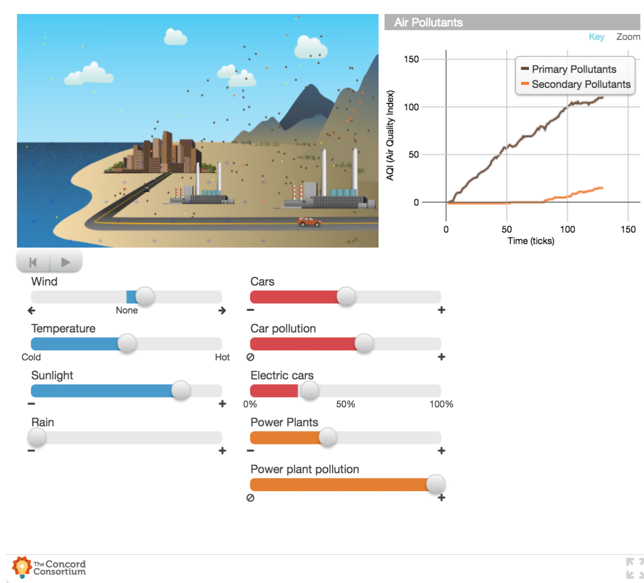

Figure 1. An Earth system model from the HAS projects. The model allows students to explore the relationship between the environment and human activity as it affects air pollution.

The **Pennsylvania Earth and Space Science Partnership (ESSP)** *(PI: Furman, Co-PI: McDonald; DUE-0962792; $9,181,723; 10/01/10 – 8/31/17)*. ***Summary of project results***. The ESSP focused on improving teaching and learning of Earth and Space Science (ESS) in the middle grades (4-9). ***Broader impacts*:** The ESSP team completed five years of summer workshops and academic-year professional development focused on plate tectonics, solar system astronomy, energy, water, and climate. The project's professional development design team developed a model with both summer-intensive and job-embedded components, grounded in Japanese Lesson Study, among collaborating groups of Earth science teachers. The ESSP team currently has a book under review with the NSTA press about this model. This model offers a pattern of teacher co-design and iterative improvement of both curricular materials and technology tools that will be a productive guide for the development of the GeoHazard project's structure. Additionally, the workshops served as a backbone for the ESSP to establish a Research Practice Partnership with a consortium of schools, including Philadelphia, Reading, York, State College, Bellefonte, and Bald Eagle Area. The project's deep partnership with these districts has resulted in the participation of 120 teachers in its extensive summer workshops. As an extension of the RPP community, the project also established the Pennsylvania Earth and Space Science Teachers Association, whose more than 800 members have made it one of the most successful state-level NESTA associations in the country. These combined efforts have developed a network of teachers in diverse districts from rural to inner city, open to innovative approaches that can be leveraged to support the new efforts of GeoHazard.

Intellectual merit*:** Primary research focused on developing learning progressions in plate tectonics and solar system formation based on more than 400 interviews around students' understanding of the causal mechanism underlying the phenomena. The team also analyzed multiple weeks of video recordings of teacher enactment in an effort to understand the impact of instruction on student learning in these two key ESS areas. These research skills will provide depth and complementary expertise to GeoHazard and bring experience disseminating work in peer-reviewed ***publications. Research on learning progressions has been published [31], with additional manuscripts in preparation. There have been two papers in practitioner journals [32], [33], and a large number of presentations at state, national, and international conferences [34]–[49].

In addition to the legacy it gains from prior HAS-related work and the strength of the teacher-related experience of the ESSP project brings, GeoHazard is also positioned to leverage powerful existing software supporting data exploration and data science education developed at the Concord Consortium. The open-source Common Online Data Analysis Platform (CODAP) (DRL-1435470) was developed under prior NSF funding. CODAP provides students a canvas for constructing data visualizations with tables, maps, and graphs. Finally, the CC and PSU teams have already begun a collaborative project extending their mutual work focused on the learning of geodynamic processes. The **Geological Models for Explorations of Dynamic Earth (GEODE)** *(PI: Pallant; Co-PIs: Lee and McDonald; DRL-1621176; $2,698,654; 8/15/16 – 7/31/20)* project is in the second year of a design and development project focused on the creation of a visualization of rich real-time earthquake data and a simulation of plate tectonic dynamic processes, as well as supporting curricula and teacher professional development. While the research is just beginning, the tools have already indicated promise in helping students understand a causal model for plate tectonics.

RESEARCH AND DEVELOPMENT DESIGN

The project will create four model-based curricular modules for middle and high school students in Earth and environmental science classes, each lasting approximately 5-7 class periods. Each module is designed to be a part of the teachers' regular curriculum. Below we describe the design principles governing the development of the materials.

The GeoHazard curriculum design principles

Design Principle 1: Use real-world natural hazards to frame the modules, making curricula less abstract and more relevant to students' lives.

Approach. Each module will be framed to explore a question that requires students' understanding of an Earth system associated with a natural hazard as well as the risk associated with a future impact. We have identified four natural hazards that are topical, socially important, and directly linked to the NGSS:

hurricanes, floods, wildfires, and earthquakes. These topics represent hazards students are likely to encounter in their daily lives, directly or indirectly (through the news). These hazards are also distributed geographically and could impact many different populations. Using real-world contexts will allow us to show how natural hazards have affected people in the past, and will lead to an increased awareness of how understanding of the science goes hand in hand with human response to these hazards.

Justification. Authentic science learning can be achieved by engaging students in the practices of scientists [16], [50] or by addressing contexts relevant to students' everyday lives [51], both of which can improve student motivation, engagement, and learning [52]; however, authentic science is not always accessible to secondary students due to their lack of knowledge and experience [53], [54]. In creating authentic experiences, Lee et al. [54] pointed out the need for translating scientists' resources and tools to make them accessible to students, as well as translating domain-specific knowledge into real-world contexts.

Design Principle 2: Use Earth systems model-based investigations as a means to learn the science underlying natural hazards.

Approach. Earth systems models are ideal for exploring natural hazards and factors that influence their formation and impact [5], [55]. GeoHazard models will simulate the dynamics of a system and be grounded in algorithms that approximate fundamental physical laws [9], [56]. Much as scientists do, students can experiment with models by controlling the variables comprising the system and conditions surrounding the system. By experimenting with the models, students can investigate natural hazards and develop complex notions of causality because the behavior of these models emerges from scientific rules. The curricula will scaffold the development of practices needed for interpreting these models. A series of increasingly complex models will help students reason about factors influencing the phenomena under study. For example, in a hurricane model, students will be able to change variables such as ocean temperatures, the location of low and high pressure in the atmosphere, wind speed, and wind direction. Students will be able to observe the emergent phenomena and explore when a change is straightforward or when a change goes beyond a linear cause and effect chain, e.g., seeing that ocean temperature is not solely responsible for the strength or path of a hurricane and its resulting impact.

Justification. Throughout K-12 schooling, students are continuously exposed to physical, biological, astronomical, and Earth systems at different spatial and temporal scales. As such, systems have been long recognized as a unifying concept in the National Science Education Standards [57] and as a crosscutting concept in *A Framework for K-12 Science Education* [58]. In the study of systems, modeling has become an important tool scientists and learners use to explore and investigate system components, interactions, and behaviors [59]. Computational models and simulations allow students to investigate systems that are difficult to manipulate by other means [60]–[63]. Virtual experiments that students can actively conduct with interactive system models are valuable for students' motivation and application and refinement of their mental models about scientific phenomena [64]. It is also important that students understand the nature of Earth science as a scientific practice, by taking an active role in trying different parameters, arrangements, and initial conditions and seeing the results of their experiments [65]–[68].

Design Principle 3: Engage in investigating real-world natural hazard data structures and patterns.

Approach. Once students learn the concepts and processes underlying the natural hazard, they are then tasked with exploring the predictability of such events and evaluating potential risks of current and future hazards. Students will use the Common Online Data Analysis Platform (CODAP) to 1) organize, analyze, and visualize data, 2) explore how changes in variables impact the system under study, 3) compare model outputs with real-world data, and 4) make predictions or conduct risk assessments. Students can, for example, investigate any of the following: the paths of hurricanes; the number of storms per year; the relationship of hurricane strength to ocean temperature; or the impact of hurricanes on people and property. Students go back and forth between the data generated from the Earth systems models and the real-world data in order to develop an understanding of how natural hazards unfold and what causes them, as well as to make predictions and evaluate future risks of the natural hazards.

Justification. Earth and Space Science (ESS) in K-12 schools is rarely considered a laboratory-based science [69]. This is in large part due to the fact that geoscience and astronomy are grounded in observational methods. The consequence is that it has traditionally been unusual for students to work with authentic data when learning ESS, which weakens their conceptual understanding of the core disciplinary ideas and fails to provide them with authentic science practices in less experimentally driven domains of science. CODAP will allow students to engage with data, as well as understand the relationship between the data and the phenomenon of interest. This dialectic between models has the potential to allow students to build robust science understandings [70]. CODAP allows authentic data to be presented in ways that are accessible and reflect underlying conceptual models (Figure 2). This is critical in ESS because it is a system science that requires taking into account many variables that cannot be controlled. For students to develop understanding of key ESS ideas related to climate or plate tectonics, for example, they need to be able to interact with models and data that represent an entire system. This allows them to see how small changes at a large scale (e.g., one degree global temperature rise) can lead to significant localized event changes (e.g., more intense hurricane).

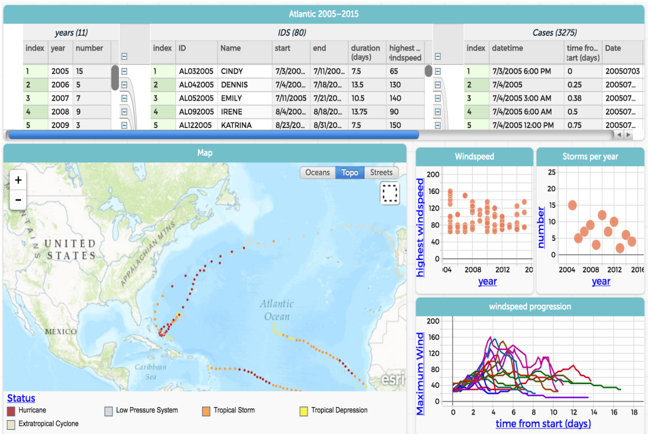

Figure 2. CODAP displaying path of hurricane and other hurricane variables.

Design Principle 4: Formulate scientific arguments to assess risks and evaluate actions.

Approach. The key to a successful approach to studying natural hazards is to consider when the impacts of a natural hazard threaten people's well-being. The extent of risk depends on the degree to which it is perceived [71]. The modules will feature specific supports to encourage students to consider the impact of an impending natural hazard and to use evidence from the exploration of the Earth system models and the real-world data to explain their assessment of short-term and long-term future risks. In the case of the hurricane curriculum, for example, students might predict the likelihood of a Category 3 hurricane hitting various populations on land over a 20-year time period.

Justification. Engaging students in scientific argumentation deepens their conceptual understanding, alters their views of science, and supports evidence-based decision making [72]–[75]. Research on scientific argumentation has grown substantially over the last few decades [76]. One aspect that has been overlooked, however, is how students treat uncertainty in formulating their arguments [77]. Uncertainty can play two roles when students construct an argument. One type of uncertainty represents students' confidence in their own knowledge and ability [78]. The other type is inherent in scientific inquiry due to measurement errors, lack of conclusive theories or models, and limitations associated with current equipment and technologies. In addition, uncertainty becomes more pronounced when the study of complex systems is concerned [79] due to the fact that any system model cannot possibly contain all variables and interactions governing the system under study [80]. Because all of the topics involve using models to predict future outcomes, issues about the validity and reliability of models and the kinds of conclusions that can be justified from the models make student understanding of uncertainty a central focus of the project. Since uncertainty in the context of natural hazards leads to risks, GeoHazard modules frame uncertainties as projected risks, or quantified uncertainty related to losses [81]. As argumentation is a central practice carried out by scientists, students' engagement with argumentation will provide insight into how scientific knowledge is constructed based on evidence [82]–[84].

An example of a day in a class using* GeoHazard *curriculum

Jada is working with two other students in her Earth science class to try to understand what influences the track of a hurricane. Jada and her classmates are particularly interested because they live near the Georgia coast and have experienced hurricanes. In addition, hurricanes have been in the news a lot, some having recently made landfall in Texas, Florida, and Puerto Rico. Jada wants to know why this year's hurricanes traveled the paths they took. Today, Jada and her group will investigate the question "How do conditions in the atmosphere affect the paths hurricanes take?" Following prompts in the curriculum, the group takes turns experimenting with an interactive hurricane model. "Let's change the locations of low and high pressure areas around the storm," one suggests. As they adjust the air pressures in the model, they observe changes in the path of the hurricane on the screen.

After they begin to understand what changes the track of a hurricane, Jada and her group turn to hurricane prediction. The curriculum introduces how scientists use historical data to create the hurricane path prediction models in order to answer the question "What paths do hurricanes take?" Using real-world data embedded in CODAP, Jada sees that each storm had a unique path and strength pattern. She sorts the data into hierarchical categories, looking for hurricanes forming in the Atlantic Ocean, and trends based on wind speed and ocean temperature. She sees some storms formed in the Atlantic and traveled towards the United States, but others formed in the Gulf of Mexico. Her group compares the paths, wind speed, and ocean temperature for each hurricane and returns to the dynamic model to experiment more with the role of ocean temperature on hurricane strength. By observing the real-world data they see that all storms are different, which makes predicting their behavior challenging. Jada and her group are then asked to develop a scientific argument to the question "What is the likelihood that a hurricane will make landfall in Georgia?"

The group claims that there is a 75% chance that a hurricane will make landfall in Georgia when a storm forms north of Venezuela. They use evidence from the model and from their data analysis to support their claim. Jada knows there are many factors that influence what happens and that making predictions for hurricane paths involves uncertainties, but she also knows that hurricanes are possible every year and there are some general patterns that emerge about their movement. Jada and her group are able to explain their claim as well as the uncertainties embedded in the claim and share their findings in a class discussion. The teacher, Ms. Chen, displays some of the students' data analysis results as a class discussion continues, helping the students interpret some of the evidence they used while developing their scientific arguments. Ms. Chen explains that students will use the model and data analysis tools next to explore hurricane landfall and the impact on homes and businesses along the coast.

Proposed module topics and model development

The four modules will address the following natural hazards topics:

Why do hurricanes form where they do? How do scientists predict their paths? There is a lot of scientific information embedded in hurricane prediction maps, which represents the probable track of the eye of a hurricane and takes into account historical tracking data and real-time atmospheric data. The path of a hurricane, and its wind strength, storm surge, and rainfall all impact human lives. In this module students explore atmospheric systems related to the formation of hurricanes, including complex interactions involving sunlight, oceans, and the atmosphere. Students experiment with variables related to ocean temperatures, the location of low- and high-pressure systems in the atmosphere, wind speed, wind direction, ocean currents, and moisture in the atmosphere. The models and data analysis are driven by publicly accessible data about historical hurricane paths and properties from the National Oceanic and Atmospheric Administration (NOAA).

What is the likelihood of a devastating earthquake occurring along different faults? Earthquakes occur every day. Earthquakes that occur near heavily populated regions or along coastlines can cause a great deal of damage to life and property. Students investigate earthquakes in terms of magnitude, intensity of ground shaking, movement along faults, and impact based on population density and building construction. Then, using United States Geological Survey (USGS) data about seismic activity, seismic hazard data, and damage estimates, students explore preparedness predictions at different locations.

Can we predict how often a flood-prone area will be flooded? How is the likelihood of a flooding event calculated? A 100-year flood is a flood event that has a 1% probability of occurring in any given year. It seems that every newsworthy flooding event is discussed in the context of the 100-year flood frequency. Flooding rivers and smaller streams deposit sediment and nutrients that are often critical for agriculture, but can also destroy infrastructure. In this module students use models to explore drainage patterns, precipitation, and how rivers respond to changing conditions, both natural (extreme rainfall) and manmade (dams and levees). Then, using data from the Federal Emergency Management Agency (FEMA) and USGS, students characterize extreme peak stream flows, frequency of higher than normal flow, and impact on different regions. Students consider the probability that any particular region would expect an extreme flooding event and explore ways in which human engineering might change risk.

Are catastrophic wildfires rare or the new norm? Reports of recent fire events suggest they are larger and more destructive than in the past. The reports also imply that these may typify fires of the future. In this module, students examine the science behind the outbreak of large and intense fires. Students use models to explore how weather, wind, and drought impact the intensity and spread of wildfires, how temperatures encourage combustion, and how plants and underbrush contribute to fires. Students look at data from FEMA and NOAA related to active and historical fires in different regions of the world and factors related to the spread of fire and the impact on various populations, and consider what humans can do to minimize the impact of wildfires.

Disciplinary Core Ideas. The four proposed modules address the following two sets of core ideas in the NGSS [67] related to Earth and Space Science: ESS3: Earth and Human Activity (ESS3.B: Natural Hazards) and ESS2: Earth's Systems (ESS2.B: Plate Tectonics and Large-Scale System Interactions; ESS2.C: The Roles of Water in Earth's Surface Processes; and ESS2.D Weather and Climate). In addition, the modules address three ***Science Practices: Developing and Using Models, Engaging in Argument from Evidence,*** *and* ***Analyzing and Interpreting Data***, as well as two ***Crosscutting Concepts: Systems and System Models*** *and* ***Patterns*** [50]. Student learning in GeoHazard will be based on exploring complex causality in models of Earth systems. We will also focus on "the ways in which data are represented can facilitate pattern recognition…which can then be used as a tool in seeking an underlying explanation for what causes the pattern to occur" (p. 86) [82].

Technology development

Earth systems models: Each module described above will need a set of unique Earth system models**.** The models are computation-intensive with visualizations ideal for exploring geoscience systems. The models simulate the evolution of a system and are based on algorithms that approximate fundamental physical laws. Everything in these Earth system models relies on computational procedures that define how the variables behave and interact with other variables within the system. Emergent phenomena are represented in the systems as variables interact over time. Because these models are for middle and high school students, the GeoHazard software will run in any browser that supports HTML5, including all school computers, Google Chromebooks, plus many tablets and other portable devices.

Hurricane hazard models: This set of models will be a canvas to explore environmental forces related to the formation and path of hurricanes. The various iterations of the model will first present variables affecting hurricanes individually: air pressure, wind, ocean temperature, and currents. The most complex version of the model will allow students to work with all variables simultaneously and reveal ways in which the physical impact of storms coincide with human populations along coasts, including hurricane path, wind speed, and storm surge.

Flooding hazard models: There will be two flooding models: one will depict a watershed and its response to extreme precipitation and sea level rise and the other will show sediment transport with respect to the speed of flow. The different scales of these related visualizations will enable students to learn about the way rivers respond to water flow on a local and regional scale to observe the ways that different factors affect the magnitude and extent of flooding and impact on people living in flood-prone areas.

Wildfire hazard models: This set of models will depict fire origin, the rate of the spread of fire, and previously burned areas. Students will first examine single variables like topography, wind, precipitation, humidity, and initial fire conditions. In the most complex model, students will adjust multiple conditions that will determine the speed and direction of wildfire movement and the impact on man-made structures.

Earthquake hazard model: This model will depict a 3D block cut-away profile view of Earth's crust that will respond to regional stress and strain forces that cause earthquakes. Students will work with variables like magnitude, fault type, locations of populations, and types of substrate. This model will be developed so that students can explore the geophysical impacts and the repercussions on structures and people living in earthquake-prone regions.

CODAP. GeoHazard will rely heavily on CODAP, which was developed at CC in prior projects. CODAP is an HTML5 web application that runs entirely in a browser. CODAP is designed to help students easily organize, analyze, and visualize data [85]. Through its drag and drop construction of visualizations, students can change what data is plotted on graphs or maps, enabling them to quickly see interesting patterns in the data. A particularly powerful feature is the way CODAP links all data views. When a user highlights selected data or elements of a graph or map, they are simultaneously highlighted in all other displayed representations. This design allows novice users to make connections across representations that are typically hidden within datasets.

GeoHazard will develop new features for CODAP. First, GeoHazard Earth systems models must be embedded in CODAP, so that the data generated from the models, including variable input and output, will be available for data exploration. Second, CODAP will need to be configured to visualize the risk of physical impact of a hazard, including the magnitude and frequency of real-world hazards, as well as geographical location and extent. Third, students will need a new feature that allows them to layer datasets to focus on geography concepts. The geography data will allow students to look at the impact of hazards on people and where they live. This geography layer will include complex mapping environments to help students visualize such things as population distribution and damage and destruction caused by hazards. Fourth, students will also need to reason about the predictability of future impacts, which will require predictive data analysis. Being able to think probabilistically with data is important and has known challenges [86]–[88]. These new features will be designed to help students interpret probability as a measure of how often an event might occur under a set of conditions; describe distributions in terms of shape and where the data are centered; use statistical reasoning to project multiple possible scenarios with varying degrees of risks, and compare risks across these scenarios.

Research Framework

Since natural hazards occur as disturbances to Earth systems, their origins, progressions, and impacts are best understood through system modeling. Although a system consists of multiple variables with defined interactions, the system behavior can often be unpredictable, calling for examining and modeling the system as a whole, rather than its parts. Modeling technologies can help learners analyze and test aspects of complex systems to develop science content understanding and make predictions. For science learners, two types of modeling can be useful: conceptual modeling with simulations and analytical modeling with real-world data.

Simulation-based conceptual modeling. Engaging students with computational models and simulations can greatly help their development of understanding [60], [89] by means of constructing, evaluating, and revising conceptual models and using models to predict and explain scientific phenomena [90]. The Earth is a system of many interacting parts; matter and energy flow in and out of the system; the system is maintained and controlled by feedback loop mechanisms [91]–[93]. It is difficult to isolate one variable in Earth's systems [94], which makes experimentation with the controlled variable strategy less feasible in teaching Earth systems concepts that cause natural hazards. Agent-based computational models [95] are thus ideal for exploring geologic systems at large space and temporal scales [82]. Much as scientists do, students in the GeoHazard project will be able to experiment with models by controlling the parameters, initial conditions, and conditions during a run. The models will have vivid graphics and run quickly, so that students can experiment, iterate, observe cause and effect, and gain insights about the system.

Data-based analytical modeling. Most data modeling tools involve interactive visualizations for secondary school students to explore complex structures of and patterns inherent in the data [96], [97]. Indeed, visual representation of data is a focus of many curricula and standards documents [98]. There have been calls for investigating what types of supports are required for students' effective use [99] and how students might interact with and manipulate more advanced data structures such as publicly accessible scientific data related to hurricanes, wildfires, and earthquakes. GeoHazard will focus student learning around data analysis and visualizing and identifying patterns in the data.

Risk-infused scientific argumentation. Scientific argumentation can provide an ideal venue to further facilitate students' use of models to develop conceptual understanding grounded in real-world data [100], [101]. Scientific argumentation can be curated as an opportunity for students to answer a real-world question related to an impending natural hazard, use data patterns, apply conceptual understanding and data analysis developed from the model, and explain how data and reasoning support their claims [102]. However, many natural hazards are difficult to forecast exactly and, therefore, involve a great amount of uncertainty in predicting future occurrences and locations, as well as in estimating impact on humans.

In GeoHazard, scientific argumentation will occur in two phases. During the model-based investigation phase, students make claims based on data in light of their understanding about Earth systems that cause natural hazards [103], [104]. In the communication phase, students compare and contrast the strengths and weaknesses of arguments based on evidence and risk [105]. No system model is an exact replica of the real-world phenomena, creating *deep uncertainty* that "results from myriad factors both scientific and social, and consequently is difficult to accurately define and quantify" [79, p. 444]. As a result, the scientists' data and models about Earth systems are "dependent upon the peculiarities of the particular experimental design, detection devices, or data-gathering procedures" [106, p. 2]. As such, drawing clear knowledge claims or predictions is almost impossible and involves a great degree of inevitable uncertainty. While current scientific argumentation in the classroom focuses on claim-evidence-reasoning, GeoHazard will also emphasize uncertainty, which we refer to as the extent to which knowledge claims are constrained by evidence generated from a particular investigation context [107]. In particular, scientific argumentation in GeoHazard will consider risks. Risk refers to "uncertainty that is measurable"[81], especially when possible outcomes are related to numerically representable losses. Note that there are always scientific uncertainties in the location a hurricane's landfall, for example. However, much less risk exists when the hurricane occurs in the middle of an ocean than when it hits highly populated areas. As a result, comparing risks in the context of uncertainties allows students to make decisions on what actions should be taken to minimize risks associated with natural hazards.

Research Questions

RQ1. ***(students' sense making between conceptual and analytic modeling)*** How do students use data visualizations to make sense of data and build and refine conceptual models about natural hazards?

RQ2. ***(students' data-based argumentation practice with risk assessment)*** How do students incorporate data from models and the real world when formulating scientific arguments? How do students use scientific uncertainty to assess risks based on their understanding of a natural hazard system? How do students quantify and explain risks to humans and compare different sources of risks?

RQ3. (***GeoHazard impact on student learning***) Do GeoHazard curriculum modules help students make gains in risk-infused scientific argumentation practice and conceptual understanding underlying natural hazards? To what extent, for whom, and under what conditions is GeoHazard useful in developing risk-infused scientific argumentation practice and conceptual understanding?

Research Plan

Research will be conducted in two phases. Phase 1 involves a series of design studies to build computational models of natural hazards and develop curriculum modules. In this phase, we will also develop and validate assessments for disciplinary core ideas and risk-infused scientific argumentation. In Phase 2, we will conduct implementation studies examining student usability of GeoHazard curriculum modules across demographics and implementation feasibility across classroom settings.

Phase 1: Design Studies (Year 1 to Year 3)

To develop models and curricular materials, studies will be conducted following the design-based research paradigm. Established learning theories, available research results, and prior designers' experiences will inform initial design choices. Iterative redesign processes in turn provide data to refine curricular materials as well as underlying theories used to develop them [108]. Each GeoHazard module will undergo three design cycles over a three-year period and include a model that is unique to the hazard featured in the module.

Design Cycle 1: GeoHazard Model Testing with Scientists, Teachers, and Student Groups. Prototype GeoHazard models will include two components: one related to an agent-based simulation model that allows student manipulation and the other related to CODAP data visualization and analysis features. Prototype models will be developed for each of the topic areas. The models will be tested at CC through several "clinical" trials and think-alouds with scientists, lead teachers, and students. Students (n = 5-6 per model) will be drawn from middle and high schools and will meet after school to participate in the think-alouds. The goal is to focus on the user experience and interaction with the modeling environment, improve the user interface, and examine whether the intended learning is accomplished.

Design Cycle 2: Curriculum Prototyping with Lead Teachers. Informed by the research literature, NGSS, and other documents, the project staff will develop performance expectations for the GeoHazard modules for content understanding, data and model sense-making, and risk-infused argumentation. We will prototype the first two GeoHazard modules in Year 1 and implement them in one teacher's classroom, along with pre- and post-tests and demographic surveys to see how the modules function. We will repeat the same process in Year 2 for the third and fourth modules.

Design Cycle 3: Curriculum Testing by Five Lead Teachers. For each module, we will work with five lead teachers and their students (approximately 400 students) to test curricular modules and assessments. The first two completed modules will be tested in Year 2 and the second two modules will be tested in Year 3. The lead teachers will be drawn from the ESSP RPP districts. Teachers will meet with staff prior to implementation for one-on-one support.

Phase 2: Implementation Studies (Year 4)

By the end of Year 3, we will have refined versions of all four curricular modules, teacher guides, and assessment instruments. In Year 4 we will solicit participation from the High-Adventure Science teachers, ESSP RPP district teachers, and the NESTA member list, and select teachers that represent diverse school settings in terms of students' language status, gender, computer experience, grade level, and school locale (suburban, urban, rural) to implement the materials. Thirty teachers will participate with each teacher enacting multiple modules. This will result in an approximate student sample size of 2,100 students (about 70 students per teacher). Ten or more teachers will implement each module so that at least 700 students will use the module. The teachers will receive a five-day face-to-face professional development experience during the summer between Years 3 and 4. The teacher professional development will be based on a model developed in the ESSP project with proven positive outcomes for teachers, both in terms of content and pedagogical learning. The summer workshops will be an integrated mix of pedagogical and science content components, along with specific work with the GeoHazard curriculum and tools. In addition, sections of the workshop will be devoted to supporting teachers in developing enactment plans based on their local contexts.

Data Collection and Analysis

During all phases of research we will collect the following data every time a module is implemented.

Pre/Post-Test Data Collection and Analysis. Students will take an online pre- and post-tests that assess their core content understanding and risk-infused argumentation. We will also collect demographic information such as gender, language, computer experience, and grade level through an online survey. Student learning outcome variables will be created for content understanding and students' risk-infused scientific argumentation. On each learning outcome variable, we will pull all student data together and apply repeated measures ANCOVA with the teacher as a fixed effect and other student demographic variables as covariates. This will allow us to examine how variations in implementation impact student learning as well as for whom GeoHazard modules are beneficial.

Module Data Collection and Analysis. Each module will include embedded prompts that elicit students' responses as 1) selecting an answer from multiple choices, 2) writing descriptions or explanations, 3) taking snapshots of models and data visualizations, 4) drawing predictions, and 5) developing risk-infused scientific arguments. Each argumentation task includes four prompts related to claim, explanation, risk rating, and risk rationale. Students' responses and their interactions with the models will all be recorded automatically by the server. Tasks and responses will be analyzed for sense-making with data and models, use of evidence in scientific argumentation, and development of risk-infused scientific arguments. See the risk-infused scientific argumentation test below for more details.

Log Data Analysis. Since log data track all student activities in the curriculum authoring system, log data provides valuable information on students' model uses and navigation in the module. Timestamped log data includes such interactions as which variables students adjust and the value of the variables, when and what students type in response to each prompt, and how long a student is running a model. Log data analysis will provide information on how much time students spend on the construction, running, and revision processes with models and the construction of data visualizations, the highlighting of data within the tool, and steps that result from notable aspects of data represented. Additionally, log data will track when students go back and forth between the data and models. Finally, the connection between students' actions and their explanations will be investigated. Log data analysis, therefore, will be used to understand students' modeling behaviors and how they link to performances on risk-infused scientific argumentation.

Assessment Validation (Year 1 to Year 2)

We will create two learning outcome variables related to understanding core science concepts about natural hazards and risk-infused scientific argumentation. Note that student modeling practices based on data and simulations will be observed and analyzed as part of log data analysis. The two instruments will be used for pre/post-tests.

Understanding of Earth systems underlying geohazards will be measured using the knowledge integration framework. Items will address students' ideas about interactions of variables of an Earth system that produces each natural hazard. Students' open-ended responses will be scored using knowledge integration scoring (KI) rubrics [109], [110], which can measure the depth of student understanding related to how and why scientific phenomena occur. The KI scoring rubrics are designed to measure students' abilities to elicit and connect relevant ideas in a scientific context [111]. Items that have used the knowledge integration framework have been validated in classroom-based trials for psychometric rigor [112], sensitivity to instruction that fosters integrated understanding of science across physical, biological, and Earth sciences [113], and learning progression in energy [114]. KI-based assessments project students' performances on a unidimensional construct according to Rasch-Partial Credit Model analysis [115] with a Cronbach Alpha value of .81 for Earth science items [7].

Risk-infused scientific arguments will be assessed using a set of items that measure the extent to which students make reasonable risk assessments and reliable claims based on available evidence from their data analysis as well as their understanding of Earth systems. In particular, we will be interested in eliciting the extent to which students recognize limitations associated with their claim and evidence-based justification (uncertainty) and how uncertainty plays a role in their assessment of risk. The uncertainty-infused scientific argumentation construct was developed for the HAS project and validated using Rasch Analysis based on Partial Credit Model (PCM) [7]. The item format for the uncertainty-infused scientific argumentation construct consists of four parts: multiple-choice structured claim, open-ended explanation, five-point Likert scale uncertainty rating, and uncertainty rationale [7], [116]. Rasch PCM results indicate that students' claims, explanations, and uncertainty rationales formulate a unidimensional construct and had an acceptable model fit. This unidimensional scientific argumentation construct had a reliability of 0.91 Cronbach Alpha. In GeoHazard, we will reformulate the uncertainty rating to a risk rating and the uncertainty rationale to a risk rationale. Three risk-infused scientific argumentation tasks will be developed per module.

Assessment Data Collection and Analysis. For each implementation, we will use pre- and post-tests to measure student gains in understanding the geosystems involved in natural hazards and gains in risk-infused scientific argumentation. Since the natural hazard understanding instrument and the risk-infused scientific argumentation instrument will need to be created for the GeoHazard project, we will design knowledge integration items and risk-infused argumentation items related to each natural hazard as the project modules are being developed. For each module, the first version of the items will be administered as a post-test in Design Cycle 2 and students' responses will be analyzed qualitatively to identify whether items elicit expected responses from students. We will modify the items according to the analysis. In Design Cycle 3, we will administer the revised items as pre/post-tests. We will analyze students' responses to the post-test (n=400) to establish the construct validity for each type of hazard. The construct modeling approach [117] consists of four steps: (1) a construct map is theorized from the relevant literature on the target construct; (2) items that elicit various levels on the construct map are selected for an instrument; (3) student responses are collected on the instrument; and (4) appropriate item response models are applied to student response data. We will use Rasch Modeling of student responses [116]-[117] to establish the validity of each instrument [120]. To ensure Rasch Modeling is appropriate, we will test for multi-dimensionality with exploratory factor analysis (EFA) using principal axis factoring with a promax rotation [121]. We will also test for local dependence [122]. We will use psychometric properties to validate the construct underlying the instrument and the items to establish a measurement scale. Moreover, since the instrument is administered as pre/post-tests, we will examine the items' sensitivity to GeoHazard modules by analyzing both pre-test and post-test. The instruments will be finalized and available for implementation studies in Year 4 for each module.

Mechanisms to Assess Success of the Project

Dr. Fuller is Executive Director of the Center for Evaluation and Education Policy Analysis (CEEPA) at Pennsylvania State University. Over the last 20 years, he has conducted scores of evaluations of educational programs and interventions and has taught research and evaluation methods. During the development phase of the project, he will use surveys, interviews, and document analyses to evaluate the utility and quality of the curricular materials, assessments, and professional development materials. Based on the results of his formative analyses, he will provide feedback to the Co-PIs as they engage in the design cycle. During the implementation phase, he will rely primarily on surveys to gather teacher perceptions of the efficacy of professional development and ongoing support as well as to gather teacher and student perceptions of the quality of the curricula. Dr. Fuller will evaluate the reports, presentations, and materials produced from this project and will meet with the Co-PIs in teleconference meetings to learn about project updates and provide feedback. Finally, Dr. Fuller will participate in the annual face-to-face Advisory Board meetings and work with the Advisory Board members in providing recommendations to the team regarding project progress.

Dissemination

The project will create a rich legacy of materials, including online curricular modules, teacher guides, and research. All curricular materials will be available in electronic form on the CC and National Geographic Society (NGS) Education websites, and linked to by the National Earth Science Teacher Association website. Once curricular modules are connected to the NGS website, NGS will promote the materials to their digital audience. The NGS website is a nationally recognized and valued resource visited by five million visitors every year. The materials will also be disseminated through the NESTA website, member lists, social media, a sponsored issue of *The Earth Scientist (TES)*, NESTA's peer-reviewed journal, and through its National Science Teacher Association (NSTA) sponsored presentations and share-a-thons. The sponsored issue of TES will be distributed to 14,000 Earth Science teachers as part of the American Geological Institute's Earth Science Week mailing. NESTA will also promote its materials through its membership, regional network and social media channels, reaching over 16,000 teachers. CC will also promote the materials through various digital channels, including blogs and social media. Additionally, all partners will promote the project through presentations and workshops at conferences (e.g., NSTA and NARST) and through articles published in peer-reviewed journals in science education (*Journal of Research in Science Teaching, International Journal of Science Education,* and *Science Education*), learning sciences (*Journal of the Learning Sciences*), and teachers (*The Science Teacher*). The *@Concord* biannual newsletter, distributed for free to over 30,000 digital and print subscribers, will be another communication venue.

Expertise

Amy Pallant will serve as Principal Investigator. She will direct the development of the models and curricular materials and be responsible for the overall coordination and budgeting of the project.

Scott McDonald, Ph.D., (Co-PI) will oversee the PSU portion of the budget, lead professional development activities, data collection, and analysis in the PA schools.

Hee-Sun Lee, Ph.D., (Co-PI), will lead research on assessment development and validation, as well as student learning of modeling practice and risk-infused scientific argumentation.

Elaine Larson (Co-PI) will manage staff at the National Geographic Society and provide expertise in media use, curriculum design, and design of materials for large audiences. She and her staff will conduct asset research and identify National Geographic media to be included in the curricula as each module is developed.

Carla McAuliffe, Ph.D., (Co-PI) at TERC will review all materials, provide insight into geoscience data and research, and be responsible for dissemination of the materials to NESTA members.

<u>Advisory Board</u>

We intend to have three advisory board meetings at the end of Year 1, 2, and 3.

Stephanie Harmon is a high school Earth Science teacher and current HAS field test teacher at Rockcastle (KY) County High School in Kentucky. She will provide real-world practical insight into classroom challenges with the materials and field test the GeoHazard materials.

Robert Crane is a professor in the department of geography at PSU. His research focuses on regional and local-scale climate change and its implications for biophysical and human systems.

Robert Gould is a professor at UCLA. He is an undergraduate vice-chair of the department of statistics and director of the Center for Teaching Statistics. He is currently writing a textbook about exploring the world with data.

Rick Duschl is a professor of science education and the Waterbury Chair for Secondary STEM Education at Penn State University. His research explores issues of the epistemology and practice of science.

Sarah McCaffery conducts research to better understand the social dynamic related to wildfire risk management. She is a researcher for the U.S. Department of Agriculture Forestry Service.

BROADER IMPACTS

In the past year, students across the United States have either experienced or seen news about a natural disaster unfolding and affecting millions of people. Whether it is a hurricane, flooding, earthquake, or wildfire, vulnerability to natural hazards does not discriminate. It has become more important than ever to ensure that students graduate from high school with a solid understanding of these hazards and their impact on humans. *A Framework for K-12 Science Education* and *NGSS* strongly emphasizes that learning about natural hazards can help humans reduce the impact of these events. Through learning about Earth's complex systems and engaging in investigations using real-world data pertaining to such events, students can gain insight into risks and risk reduction measures. The GeoHazard project will provide new knowledge on how to teach Earth science phenomena involving complex systems, integrate systems science and modeling into a natural disaster curriculum, and the role of risk analysis as it relates to developing scientific arguments. The project can provide a curriculum exemplar for how Earth systems models and data visualization tools can be integrated into learning opportunities. Finally, providing robust geoscience concept knowledge to our youngest generation is an investment that can help safeguard their future. The project will create a rich legacy of materials, including online curricular modules, teacher guides, and research publications. Project materials will be developed with close attention to the needs of diverse students and will be implemented in a wide range of schools, including those that serve underrepresented students. The online materials will be made available for free to all future learners, teachers, and researchers beyond the participants outlined in the proposal. GeoHazard will be promoted and distributed to national audiences through all the partners' websites and social media connections.