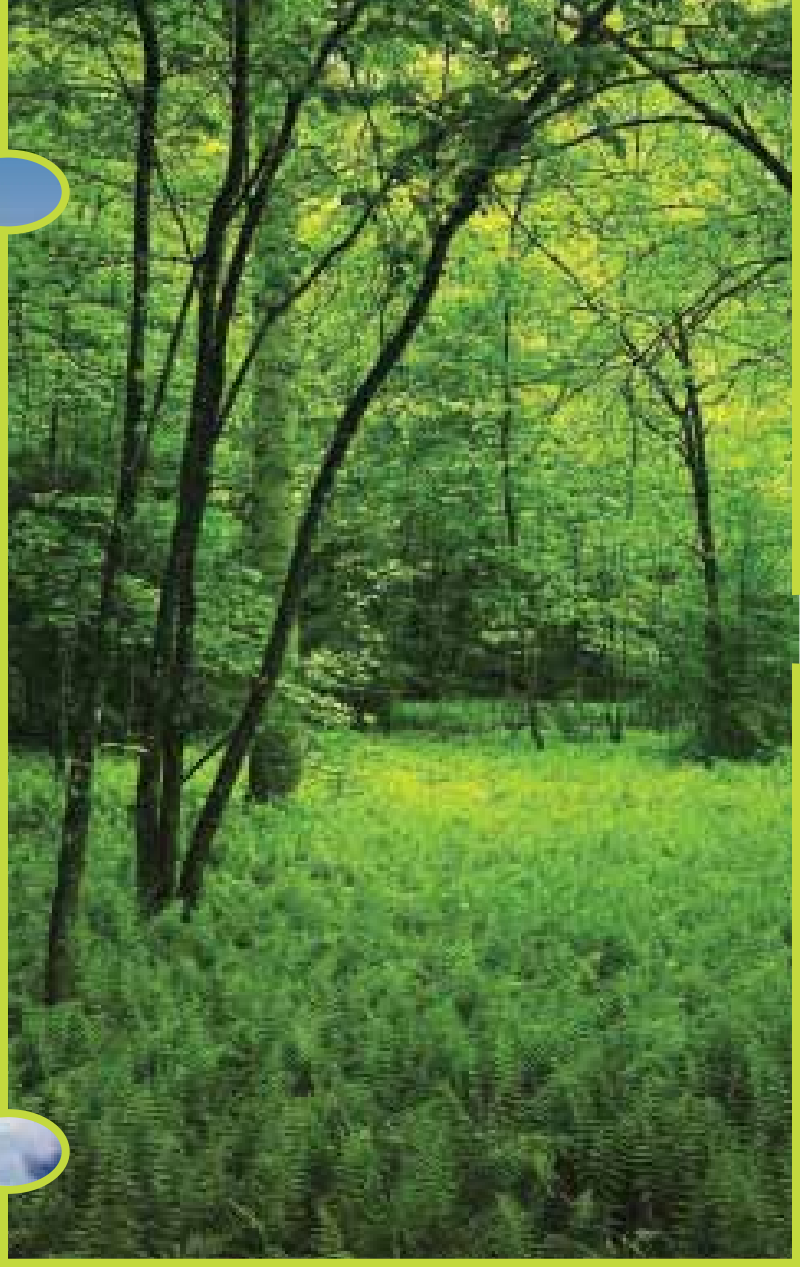


CONNECTING EARTH SYSTEMS:

Developing Holistic Understanding Through the Earth-System-Science Model

by Valoree Gagnon and Heather Bradway

The planet Earth has a long list of environmental issues: expanding droughts and wildfires; escalating frequency and strength of tornadoes and hurricanes; spreading invasive species; and increasing numbers of endangered species. These unprecedented concerns make headlines every day all over the world, however, helping middle school students make sense of contemporary events as they relate to Earth science can be a challenge for any teacher. For many years, Earth science concepts have been taught as thematic units with lessons in nice, neat chapter packages complete with labs and notes. But compartmentalized Earth science no longer exists, and implementing teaching methods that support student development of holistic understandings can be a time-consuming and difficult task.

While participating in the National Science Founda-

tion's Global Watershed GK–12 program, we found ourselves reading current events in preparation for a "human impacts" lesson plan. It was during this search that we found a model that easily demonstrates Earth systems and their interactions, one that teaches conceptualizing Earth as a holistic system. While using the model to teach human impacts, we realized students' ability to apply the idea of four Earth systems continually interacting was valuable for additional Earth science learning. In diverse ways, we began incorporating the model into existing lessons. In this article, we begin with a brief description of the model's history and how the model is supported by teaching standards. Next we provide an overview of the ways we introduced the model into our classroom. And finally, we conclude with ways we incorporated the model into additional eighth-grade Earth science curricula.

Earth-system science: History and future

The foundation of Earth science curricula is learning about the four Earth systems: hydrosphere, atmosphere, biosphere, and lithosphere. The cyclical model illustrates each system continuously interacting with all others. To help students realize connections among systems, we used a model called Earth-system-science (ESS) analysis. The ESS model is similar to a concept map (see Figure 1). It includes four spheres, representing the four Earth systems, which are placed around a centered sphere, representing an Earth event. The model is linked together by 10 two-way arrows: Each Earth-system sphere is connected to the Earth event (4 arrows), and all Earth systems are connected to each other (6 arrows). The ESS model was developed by the NASA Advisory Council's Earth System Sciences Committee in 1983,

and in a 1988 report, the committee published for the first time how Earth systems interact using the ESS model (ESSC 1988). The model is currently used by multiple organizations, from the United Nations Environment Programme to the Intergovernmental Panel on Climate Change (Stewart 2005). Today, tens of thousands of scientists contribute to Earth-system science globally.

The ESS model is also supported by *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas,* a report published by the National Research Council (2012) that divides the study of Earth and space sciences into the following core ideas:

- Earth's place in the universe
- Earth's systems
- Earth and human activity

The ESS model addresses two of the three core ideas by having students identify cause-and-effect relationships within Earth's systems; analyze natural and human-caused events; and recognize that humans are indeed a part of the biosphere and therefore interact with all of the Earth systems. In addition, many crosscutting concepts are supported using the model in the science classroom. ESS allows students to engage in unifying themes found across the sciences and engineering such as the following: cause and effect; systems and system models; energy flow and matter; and stability and change. Using the model throughout the curriculum reinforces the core ideas put forward by the National Research Council.

Using the ESS model in the classroom

We applied the ESS model in our teaching through the following three steps.

Step 1: Introduce the four Earth systems

First and foremost, we knew that using the ESS model would require our students to be able to recognize the Earth's four systems and their primary characteristics. To establish this understanding early in the year, students were asked to respond to the questions outlined in an Earth-system-science handout (see Figure 2) during the first week of school. The following questions from the handout were intended to elicit what students know and what they would like to know about Earth science:

FIGURE 1 Earth-system-science model developed by NASA and used as a tool with secondary students

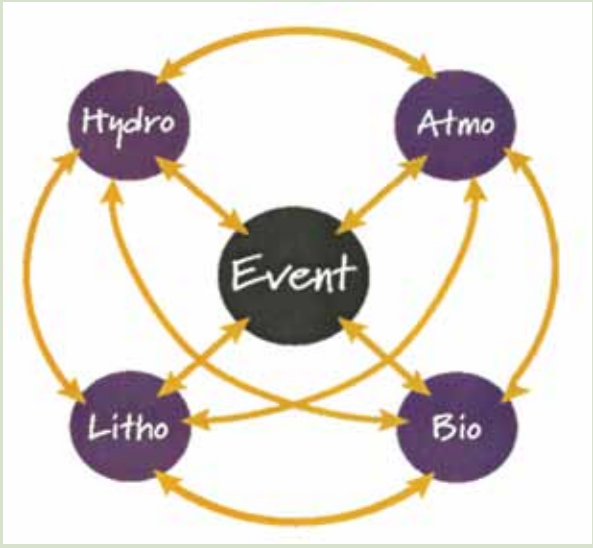


ILLUSTRATION USED WITH PERMISSION OF EXPLORING THE ENVIRONMENT (*WWW.COTF.EDU/ETE*).

1. When you think of "Earth science," what comes to mind?
2. In what ways have you learned about the Earth in the past? Think about trips, other classes, and the news.
3. Have you heard of "Earth systems"? What have you heard? What are some system names and characteristics?
4. What are some questions about the Earth that you would like answered?

In the following exercise, we wanted students to begin thinking about Earth science (questions 1 and 2) in terms of Earth systems (question 3). We began by asking students for their individual responses to questions 1 and 2 and listed those responses on the board under the heading "Earth Science." We also asked students to record their classmates' responses to their own handout. Next we drew on the board the four model spheres representing the four Earth systems, explained the basic representation, and proceeded to

FIGURE 2 Earth-system-science student handout used in step 1

Earth-system-science concept map

Name: _____
Hour: _____

Directions: Please read and answer the following questions by completing each of the following requirements (10 points). We will have a class discussion and complete the concept map together as a class based on your responses (10 points). This assignment will be 20 points total.

1. When you think of "Earth science," what comes to mind? (2 points)
2. In what ways have you learned about the Earth in the past? Think about trips, other classes, and the news. (2 points)
3. Have you heard of "Earth systems"? What have you heard? What are some system names and characteristics? (4 points)
4. What are some questions about the Earth that you would like answered? (2 points)

question 3. Beginning a new list headed "Earth Systems," we recorded their responses on the board as students added the contributions to their handouts. Then we asked students to think about the similarities and differences in the list and how we could organize their Earth-system list into four categories. Based on this discussion, students (re)discovered as a class each Earth-system name and labeled each system with its primary characteristics (defined as liquid, gaseous, solid, and living Earth; or water, air, land, and life). Students will need varying teacher guidance to accomplish labeling their model. For example, it will be useful for teachers to ask students where they've previously heard the words *hydro, bio,* and *sphere,* or to ask them to point to the atmosphere. Upon completion of labeling the model with Earth-system names and characteristics, students were asked to revisit the Earth science list written on the board. We explained to students that each response could be placed somewhere on their model. Together as a class, we decided one by one where the first three responses belonged on the ESS model up on the board. (For example, students decided to place "volcanoes" near the lithosphere; "storms" near the atmosphere; and "ocean" near the hydrosphere. The exercise will vary depending on student responses, but these three were common ones among our students.) To complete this exercise, we had student pairs place the remainder of the Earth Science responses within their ESS models on their handouts.

Many students discovered that some of their responses did not fit neatly into one Earth system but overlapped in two or more, an observation worth commending. We asked students to place overlapping concepts on the ESS model as best they could. A student-led discussion ensued, during which students explained the ways in which they resolved overlapping concepts. When students resolved overlaps by placing their response between two Earth systems, we would draw a single two-way arrow (see Figure 1) on the board model to illustrate. This lesson was accomplished in one class period and closed with a class discussion based on the following questions:

- Does the Earth actually exist as four separate systems? Why or why not?
- Why would learning about Earth systems be important?

Step 2: Add an "event" to the four Earth systems

The next stage of learning the ESS model involves tying in an event, either of natural or human origin, to the Earth systems and further exploring connections between Earth systems and Earth events as cause-and-effect relationships. Arrows are used in the model as shown in Figure 1 to help students visualize the connection between an event and the Earth systems. The arrows in the model point in two directions because ongoing activity in the systems can also cause an event. By using a local, regional, or global event to generate focus on an Earth science concept, teachers help students begin to understand how a seemingly minor event can have an impact on the Earth in major ways, affecting all of its systems.

We engaged students in the recognition and identification of Earth science events by using their prior knowledge of headline news stories and current events

from the previous lesson and discussion. The following questions were intended to elicit what students already knew about Earth science events, even though they may not have recognized them as such:

- What do you think of when you hear someone talk about an Earth science event?
- Where do you hear about Earth science events? What do you hear?
- Have you ever witnessed an event? Where? What did you see?

Students contributed ideas such as earthquakes, droughts, and a variety of storms; all student responses were recorded on the board under the header "Event," and students copied this list in their notebooks, as well. We continued the discussion by asking students to explain the term *change* and to provide an example of change in an Earth system. We added to their explanations by describing an event as when a change takes place on Earth, and clarified change as subtle or sudden, short or long term, or positive or negative. To facilitate an understanding of system connections, we used their Event contributions and asked the following questions based on cause and effect:

- What do you think were some of the causes? In which Earth systems?
- Do you think the event was natural, human caused, or both?
- What kinds of changes happened during the event? After the event? In which Earth systems(s)?

We added many student contributions to the ESS model on the board, near and between the systems as they indicated. Students began to recognize multiple "correct" answers, as cause-and-effect relationships can be numerous. To further explore Earth-system and -event connections, we analyzed two real-world event examples using the ESS model. For the first event, students watched a Google Earth tour of the planned construction of the Belo Monte Dam in Brazil (IR&AW 2010), after which we drew the complete ESS model on the board, labeled the Earth systems and event, and asked students the cause-and-effect questions listed above. We wrote the first few student responses on the board and then had several students come to the board and add a cause or effect to the model.

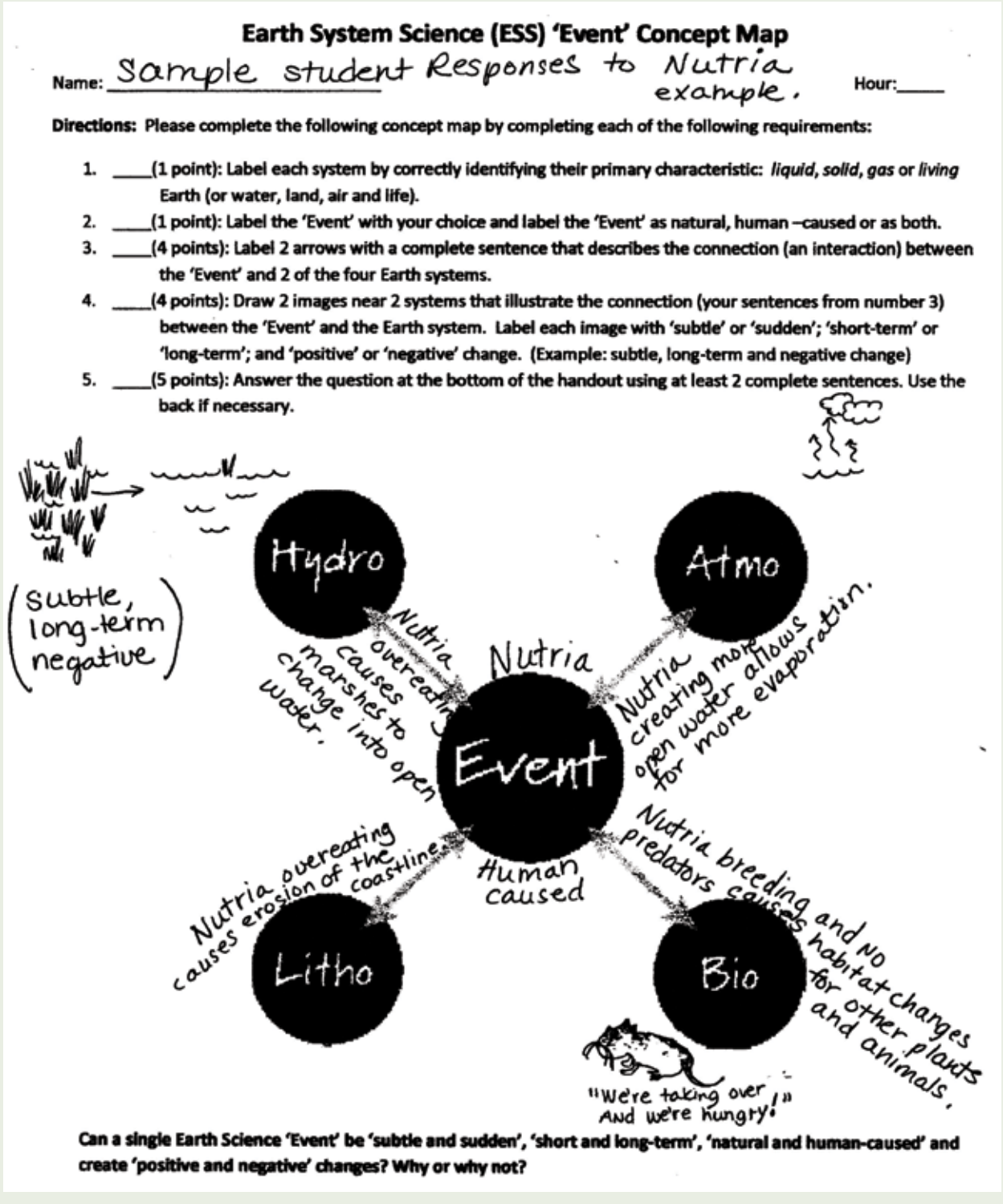
The second event we explored was the introduction of nutria on the Gulf coastline (LDWF 2007; USGS 2000). We began by displaying a picture of the "mouse beaver," as it is known, and gave a brief description: a 12-pound vegetarian that consumes 25% of its body weight per day, whose only predator is the alligator, and that is a year-round breeder. Next we shared the background information on the purposeful introduction of nutria to the Louisiana coast. In 1937, nutria were intended to control problem plants (water hyacinth and alligator weed) and, at the time, were viewed as a possible fur source. But they quickly spread into 15 surrounding states that have similar marsh habitats. Since their introduction, nutria have destroyed miles of coastline as well as agricultural fields; the destruction they cause continues to the present day. A recent study showed that the best way to control the population is to pay nutria bounty hunters for the animals' pelts. Students were asked the same questions above, based on cause and effect, about this entertaining example. Figure 3 shows the assignment given for this portion of learning the ESS model, as well as student responses during class. We accomplished step 2 in two class periods.

Step 3: Tools for developing holistic understanding through Earth-system connections

The final step in teaching and learning through the ESS model is an ongoing process that stems from three basic questions (we call them *guiding questions*) and a list of descriptive interactions that will grow with student knowledge (we call these *connection keywords*). Using these questions and keywords as tools assists students with viewing the Earth systems holistically by understanding how or why an event specifically affects a system or systems or how one Earth system influences another system during an event as they use the ESS model throughout the school year. In addition to giving students the tools, we also introduced the history of the model to demonstrate to students that scientists from NASA, as well as other well-respected organizations, use the model to understand Earth changes and events.

We explained to students that because scientists begin investigating system connections by thinking

FIGURE 3 Student responses for the nutria-event class discussion using the handout provided for step 2



Earth System Science (ESS) 'Event' Concept Map

Name: Sample student Responses to Nutria example. Hour:____

Directions: Please complete the following concept map by completing each of the following requirements:

1. ____(1 point): Label each system by correctly identifying their primary characteristic: *liquid*, *solid*, *gas* or *living* Earth (or water, land, air and life).
2. ____(1 point): Label the 'Event' with your choice and label the 'Event' as natural, human –caused or as both.
3. ____(4 points): Label 2 arrows with a complete sentence that describes the connection (an interaction) between the 'Event' and 2 of the four Earth systems.
4. ____(4 points): Draw 2 images near 2 systems that illustrate the connection (your sentences from number 3) between the 'Event' and the Earth system. Label each image with 'subtle' or 'sudden'; 'short-term' or 'long-term'; and 'positive' or 'negative' change. (Example: subtle, long-term and negative change)
5. ____(5 points): Answer the question at the bottom of the handout using at least 2 complete sentences. Use the back if necessary.

Can a single Earth Science 'Event' be 'subtle and sudden', 'short and long-term', 'natural and human-caused' and create 'positive and negative' changes? Why or why not?

about cause-and-effect relationships, we would also use these same tools, or guiding questions, to help them understand how one Earth system is connected to another:

- What changes?
- How does it change?
- Or why does it change?

We outlined these questions on the board under the header "Guiding Questions" and asked students to write them in their notebooks. Next we explained that scientists discover Earth-system connections by thinking about the following connection keywords:

- *Causes, effects*
- *Increases, decreases*
- *Changes, impacts*

Again, we outlined these keywords on the board under the header "Connection Keywords" and asked students to write them in their notebooks. Then we asked students to contribute to the list of connection keywords by using them in a phrase. Some of the phrases students added were *destroys something, hurts or damages different species,* and *saves an animal and benefits people.*

Using these guiding questions and connection keywords out loud, we conducted a complete ESS model analysis with students. The event example we used, the 1988 Yellowstone National Park forest fire, was an actual analysis conducted by scientists (CET 2005). (The analysis can be found in its entirety at the CET website listed in the References.) The phrase "1988 Yellowstone Forest Fire" was written on the board and circled. Students were instructed to copy everything into their notebooks and told that at the end of this lesson they would have to choose their own event and use the model to show Earth-system and -event interactions. Next we asked for a student volunteer (at this point it only took one) to draw the four spheres on the board, label them, and use connecting arrows just like those shown in Figure 1. The following part of the analysis involved asking students to use phrases showing how the event affected a system or how a system would affect another system because of the event. We asked for student volunteers to write that phrase on the appropriate arrow on the model. If students became stuck, we reminded them to use their tools: Ask the guiding questions aloud when moving from one system connection to the next, and point out the use of connection keywords. A sample of this activity and possible responses is found in Figure 4. When our analysis was complete, we reiterated the point to students that our ESS model was simply a partial list of system interactions. While working on the Yellowstone event and after four different student volunteers had labeled two event-to-system and two system-to-system interactions with phrase descriptions on the arrows on the board, we began to dissect several of their responses for cause and effect. This is important for two reasons: First, it ensures a saturated description (using the keywords), and second, it provides students a way to check that their description is complete. This was accomplished by having multiple students come up to the board to underline keywords such as *increasing* and *impacts*, and then circle and label specific words and phrases as cause or effect. (Two examples: [1] *Increasing* was underlined; *fire releases CO2 and other gases into the air* was circled/labeled *cause*; and *increasing pollutants* was circled/labeled *effect*. [2] Cause was underlined; high heat from fire was circled/labeled cause; rocks to break apart was circled/labeled effect. Details of the analysis are shown in Figure 4.) Students were then evaluated on their own ability to create an ESS model based on an event of their choosing; use the guiding questions and connection keywords to describe interactions; and dissect the cause-and-effect relationships through the circling and labeling exercise. (Students chose an event from their step 2 notes under Events.) This lesson was completed in two class periods, and its closure included an explanation of assessment instructions and a brief discussion of the following questions (see Figure 4):

- Why is it important to describe Earth-system interactions using cause and effect? Who would this be valuable to? And why?

Incorporating the ESS model in Earth science curricula

Because we valued students viewing the Earth and understanding its systems holistically, we invested more time implementing the ESS model throughout the school year in various ways. We incorporated the

FIGURE 4 Sample responses to step 3, with keywords underlined and cause-and-effect phrases circled and identified

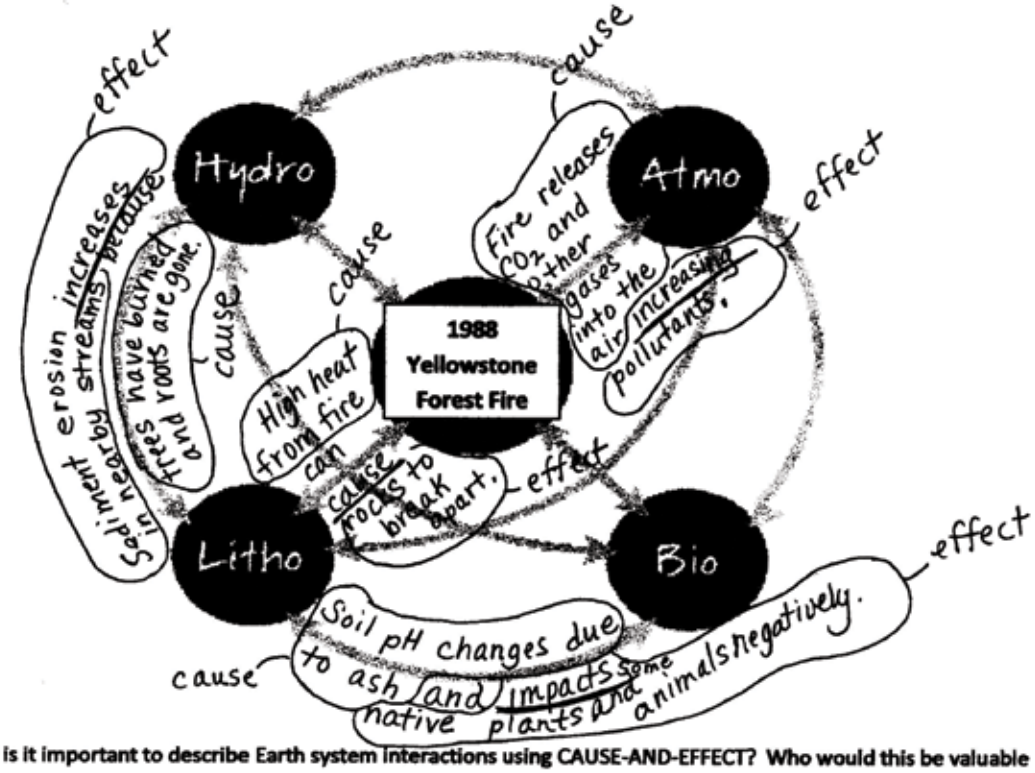
Earth System Science (ESS) System Interactions

Name: SAMPLE Hour:_____

Directions: Using what you have learned about the 1988 Yellowstone forest fire, complete the ESS model below by writing **two event** interactions and **two sphere** interactions. Use complete sentences. Remember to underline the keyword in each sentence and to circle and label phrases found in the sentences as a *cause* or *effect* (you will find both).

Some Sample Keywords	***Cause and Effect***
Causes, effects	Cause- comes first, origin of the event, start
Increases, decreases	Effect- happens after, occurs as a result of something else
Changes, impacts	

1. ____(2 points): Label two arrows with a complete sentence that describes the connection (an interaction) between the 'Event'.
2. ____(2 points): Label two arrows with a complete sentence that describes the connection (an interaction between the 'Spheres'.
3. ____(4 points): Keywords have been underlined with each event and system interaction.
4. ____(8 points): BOTH *Cause and Effect* have been circled and labeled with each event and system interaction.
5. ____(2 points): Answer the question at the bottom of the handout using at least 2 complete sentences. Use the back if necessary.



Why is it important to describe Earth system interactions using CAUSE-AND-EFFECT? Who would this be valuable to? And why?

ILLUSTRATION USED WITH PERMISSION OF EXPLORING THE ENVIRONMENT (*WWW.COTF.EDU/ETE*).

ESS model when teaching large-scale events such as erosion, volcanic activity, climate, and oceanography. Also, we had students read about current events and view documentaries as another way to use the model to gain scientific understanding of ongoing environmental issues. NASA has an excellent resource called the Gateway to Astronaut Photography of Earth (see Resources), which shows hundreds of searchable photos taken of Earth from space. Students were able to utilize the ESS model as they viewed assigned images and asked to write about how an event (e.g., forest fire, drought) affects Earth systems. Finally, we gave students an imaginary event, such as "What if the Earth had no Moon?," and asked them to write a response using the ESS model. Throughout the year, students created ESS models individually, in groups, and as part of student-led class discussions.

All of these student ESS activities enhance the goals of the next generation of science standards for Earth science. From Earth to space and from incremental changes to cataclysmic events, the model traces cause-and-effect relationships, supporting students in holistic understandings of Earth science through Earth-system connections. The ESS model is both a solid and a fluid structure, an organized and creative framework. It connects students and teachers to real-world issues, science, and the existence of Earth as a series of interacting and connected systems. ■

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Valoree Gagnon (*vsgagnon@mtu.edu*) is a graduate student in the environmental and energy policy program at Michigan Technological University in Houghton, Michigan. **Heather Bradway** *(heabrad@hancock.12.mi.us)* is a science teacher at Hancock Middle School in Hancock, Mighigan.

References

Center for Educational Technologies (CET). 2005. Exploring the environment: Yellowstone fires. Wheeling, WV: Wheeling Jesuit University/NASA Classroom of the Future. *www.cotf.edu/ete/modules/yellowstone/YFmain.html.*

Earth System Sciences Committee (ESSC). 1988. *Earth system science: A program for global change.* Washington, DC: National Aeronautics and Space Administration.

International Rivers and Amazon Watch (IR&AW). 2010. Sigourney Weaver narrates Google Earth tour of Belo Monte Dam. *www.internationalrivers.org/resources/sigourney-weaver-narrates-google-earth-tour-of-belo-monte-dam-3444.*

Louisiana Department of Wildlife and Fisheries (LDWF). 2007. Nutria population dynamics—A timeline. *www.nutria.com/site2.php.*

National Research Council. 2012. *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas.* Washington, DC: National Academies Press.

Stewart, R.R. 2005. Our ocean planet: Oceanography in the 21st century. College Station, TX: Department of Oceanography, Texas A&M University. *http://oceanworld.tamu.edu/resources/oceanography-book/contents2.htm.*

United States Geological Survey (USGS). 2000. Nutria, eating Louisiana's coast. Lafayette, LA: *USGS/National Wetlands Research Center. www.nwrc.usgs.gov/factshts/020-00.pdf.*

Resources

Earth-system science—*www.cotf.edu/ete/ESS/ESSmain.html*

The gateway to astronaut photography of Earth—*http://eol.jsc.nasa.gov*