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Using Interactive Technology to Support Students' Understanding of the Greenhouse Effect and Global Warming

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Abstract In this work, we examine middle school students' understanding of the greenhouse effect and global warming. We designed and refined a technology-enhanced curriculum module called *Global Warming: Virtual Earth*. In the module activities, students conduct virtual experiments with a visualization of the greenhouse effect. They analyze data and draw conclusions about how individual variables effect changes in the Earth's temperature. They also carry out inquiry activities to make connections between scientific processes, the socio-scientific issues, and ideas presented in the media. Results show that participating in the unit increases students' understanding of the science. We discuss how students integrate their ideas about global climate change as a result of using virtual experiments that allow them to explore meaningful complexities of the climate system.

Keywords Technology-enhanced instruction · Middle school students · Greenhouse effect

Introduction

Technology-enhanced learning environments using dynamic visualizations and virtual experiments can provide instruction and scaffold learners as they learn new scientific information and help them generate sound mental representations (Linn et al. 2006). However, students need guidance to use the technology effectively (Edelson et al. 1999). Education researchers understand that as new technologies (like dynamic visualizations) are adopted into classrooms, studies must address the best practices and conditions for supporting teaching and learning with them (Hegarty 2004).

Visualizations generally provide students with more information and involve higher levels of interactivity than instruction presented in text or lecture format. Therefore, the visualizations and instruction must be carefully designed in order for them to be effective tools for learning (Morrison et al. 2002). In particular, students need help to focus their attention as they participate in the learning environment and interact with visualizations and simulations (Gobert and Pallant 2004). This guidance reduces the processing requirements of dynamic visualizations and helps to facilitate learning (Sweller et al. 1990). In addition to providing innovative instruction, tools, and activities, well-designed technology-enhanced environments can also provide the guidance needed to engage in productive learning (Linn et al. 2006).

This manuscript presents research conducted with a curriculum module designed with the aforementioned issues in mind. The curriculum module, *Global Warming: Virtual Earth,* features an interactive visualization of the greenhouse effect that helps students understand the science of the greenhouse effect and global warming. The visualization supports learning in two ways. Students can use it to observe unseen processes that underlie the phenomena, and they also manipulate the visualization to learn about five variables involved in the greenhouse effect: solar energy, infrared energy, greenhouse gases, clouds, and

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albedo. The module activities support students to conduct controlled, virtual experiments and explore interactions and transformations among the variables.

The focus of this work is to look at whether a technology-enhanced curriculum module can help middle school students engage in inquiry activities (experimentation) to learn about complex science topics (the greenhouse effect and global warming). In order to facilitate learning via experimentation, we rely on principles outlined in the knowledge integration framework to design the learning activities and guide students' virtual experimentation (Linn 2006).

The Knowledge Integration Perspective on Learning and Instruction

Knowledge integration (Linn 2006) is a cognitive perspective of learning that is consistent with theories of teaching and learning promoted by the learning sciences (Bransford et al. 1999). This perspective focuses on knowledge as a collection of ideas that interact with each other to form understanding (Özdemir and Clark 2007). It emphasizes the ideas that students bring to a situation via their own experiences and observations and proposes ways that instruction can take advantage of the ways that learners naturally develop new knowledge (Linn 2006).

The knowledge integration (KI) framework outlines four processes that help students develop an integrated understanding of science concepts and processes. The processes include eliciting students' ideas, introducing new ideas, developing criteria for evaluating ideas, and sorting and reorganizing ideas (Linn and Eylon 2006).

The first process, *eliciting ideas*, involves encouraging students to express their initial ideas about scientific concepts and phenomena. Engaging in this process allows students to consider their own ideas as they learn new ones so that they are more likely to form new connections. This helps students to develop an integrated understanding of scientific phenomena (Linn 2006). At the beginning of the module, students are asked to express their ideas on what they already know about the greenhouse effect and global warming. We also elicit students' ideas by asking them to generate hypotheses about how they think different components in the greenhouse effect (i.e., greenhouse gases, clouds) affect the earth's temperature. The second process, *introducing new ideas,* occurs as students read new information included in the module and primarily as they engage in virtual experimentation activities with the greenhouse visualization. Students examine the roles of different variables by making adjustments in the visualization, observing changes in the earth's atmosphere, and recording changes in the earth's temperature. The virtual experiments provide evidence for students to develop new ideas and insights related to the greenhouse effect. Experimentation activities motivate students to not only add new ideas but to reconsider their existing ideas. For instance, since students are asked to make predictions based on their existing ideas, they are more apt to form connections between these and new information from the virtual experiments (Linn 2006). The third process, *developing criteria for sorting ideas*, involves helping students develop criteria to distinguish between normative and non-normative ideas. In the global warming module, students evaluate results from their virtual experiments with the visualization. This involves comparing the data and observations with their initial predictions or ideas. As they do this, they develop criteria for evaluating new information as well as their prior ideas. Students will become more aware of gaps in their knowledge as they see unfamiliar variables like albedo and infrared energy. They will recognize some ideas that overlap with their pre-existing knowledge (i.e., that an increase in the concentration of greenhouse gases increases the Earth's temperature), and recognize and resolve ideas that contradict their initial ideas (i.e., that the greenhouse effect is a naturally occurring phenomenon). These actions will stimulate them to seek connections among their ideas. A culminating activity at the end of the module requires students to generate a plan for reducing their contribution to global warming based on the new information they have learned during their participation in the module activities. This engages them in the fourth process, *sorting and reorganizing their ideas*. Students reflect on new information and their previous ideas to develop a deeper, integrated understanding of the greenhouse effect and global warming. As they do this, they will use the criteria they developed to promote some ideas and demote others.

In addition to informing instruction, the knowledge integration perspective also describes levels of understanding. According to the KI perspecitve, when students learn, they develop more normative ideas that are meaningfully linked together producing an integrated understanding of the target phenomena or concepts. In this work, we use the KI perspective to examine changes in students' understanding of the greenhouse effect and global worming.

To illustrate knowledge development, the knowledge integration highlights the *links* that students form between new and existing ideas. Students use the criteria developed during learning activities to re-evaluate and re-organize their knowledge to incorporate new ideas. As they do this, they form links among ideas in their repertoires. The learning outcome data presented in this paper are analyzed using knowledge integration scoring rubrics. These rubrics are used to code students' responses to open ended prompts about the greenhouse effect. Responses are coded based on the presence of normative ideas and links that students have prior to and following their participation in the curriculum module.

Our instruction objectives are to help students develop integrated ideas about the greenhouse effect and global warming by understanding the energy balance between solar energy and infrared energy, the absorption and reflection processes of the Earth's surface, and the interactions of greenhouse gases and infrared energy. Our research objective is to examine students' understanding of these ideas prior to and following their participation in a technology-enhanced curriculum module that features an interactive visualization of the greenhouse effect.

Students' Scientific Knowledge: Ideas about Global Warming and the Greenhouse Effect

Students bring naïve ideas about the greenhouse effect and how global warming occurs to science class. These ideas influence the way that students acquire new knowledge (Vosniadou 1994; Vosniadou et al. 2004).

Andersson and Wallin (2000) conducted a study focusing on high school students. They found that these students had several different representations of the greenhouse effect. Many confused the greenhouse effect with global warming and described it by listing the causes of global warming. Others confused the greenhouse effect with "the ozone effect" (Andersson and Wallin 2000). This confusion about the relationship between the greenhouse effect and the ozone is common (Francis et al. 1993; Meadows and Wiesenmayer 1999; Rye et al. 1997). Data from Meadows and Wiesenmayer's (1999) study indicate that some students have incorporated this misconception into their knowledge frameworks of global warming and use it to reason about all issues related to the global warming phenomenon. Other work shows that some pre-service teachers also attribute the cause of climate change to the depletion of the ozone layer (Papadimiriou 2004). However, some students do have correct notions about the science underlying the global warming phenomenon. Boyes and Stanisstrett (1993) presented 36 statements about the greenhouse effect to students ranging in age from 11 to 16 years old. They were asked to indicate whether the statements were correct or incorrect. Most students correctly indicated that carbon dioxide enhances the greenhouse effect and that an enhancement of the greenhouse effect leads to global warming (Boyes and Stanisstrett 1993).

In the work presented in this paper, students initially learn about solar energy, heat energy, and infrared energy. Then they build on this understanding and learn about how greenhouse gases and albedo impact the temperature of the Earth. Finally, they put all of these ideas together and make inferences about the impact of the relationships to understand the greenhouse effect and global warming. The goal is for students to learn about the role of each concept in the greenhouse effect and to understand how they interact to create the greenhouse effect. The activities also help students understand the relationship between the greenhouse effect and global warming. We define complete normative representations as those that include evidence of *integrated* target ideas. We measure students' representations by analyzing their responses to a series of open-ended questions about the concepts covered in the module.

Methodology

Research Design

The main research question is, "How does students' understanding of the greenhouse effect and global warming change after participating in a technology-enhanced learning environment featuring virtual experiments with an interactive visualization?" This research is part of an iterative design based research project (Barab and Squire 2004; Brown 1992; Wang and Hannafin, global warming and to refine the *Global Warming: Virtual Earth* curriculum unit. Students participate in the week-long unit during their science classes. The analyses focus on characterizing students' understanding following their participation in the curriculum unit activities.

Students participate in an eight-question, paper and pencil assessment prior to and following participation in the unit creating a matched sample comparison. A series of matched sample t-tests are used to determine the degree of significance between pre and post test performance.

Participants

Five teachers from three schools on the west coast and two schools in the southeastern US enacted the curriculum unit in their sixth grade science classes. The teachers each had at least 2 years of experience using our curriculum units in their instruction. Each teacher received targeted professional development support (Varma et al. 2008). The professional development activities included meetings to introduce the overall WISE learning environment and the *Global Warming: Virtual Earth* curriculum unit. Teachers also received mentored classroom support to help them incorporate the activities in their instruction (Varma et al. 2008). One hundred ninety sixth grade students (98 males and 92 females) participated in the unit activities and the pre-post assessments. Table 1 presents a demographic summary of the participants.

Table 1 Participant demographics

School	Number of teachers	Student ethnicity					SES
		White (%)	Black (%)	Asian (%)	Hispanic (%)	Other (%)	Free/reduced lunch (%)
A	1	73	11	12	4	0	42
B	2	16	33	6	24	21	55
C	1	52	3	11	27	7	17
D	1	49	18	7	26	0	62

The category "Other" includes Filipino, American Indian, Alaska Native, and Pacific Islander Students

The Curriculum Unit

The *Global Warming: Virtual Earth* unit was created in the Web-Based Inquiry in Science (WISE) learning environment. The WISE environment combines internet information and resources with visualizations to provide meaningful inquiry instruction experiences to students and teachers. Students navigate through curriculum units by following steps in the "inquiry map" on the left side of the screen. They can move between activities, respond to embedded reflection notes, get hints, access their on-line journal, and review their work. The main content of the selected step appears in the larger window on the right. Figure 1 shows a screenshot of the curriculum unit in the WISE Environment

The curriculum unit includes six main activities. In the first activity, students are introduced to the overall learning goal of the unit. They view short video clips as an introduction to the global warming phenomenon and calculate their ecological footprint using an on-line ecological footprint calculator (Islandwood 2010). In the second activity, students learn about the Earth's energy balance and observe the energy transformation depicted in the greenhouse visualization. The third and fourth activities focus on using the greenhouse visualization to learn about greenhouse gases, clouds, and albedo. Figures 2 and 3 show screenshots of the visualization.

In the third activity, students conduct experiments with the visualization to learn about greenhouse gases. The fourth activity is a jigsaw activity in which half of the students conduct experiments to learn about clouds. The other half conducts experiments to learn about albedo. Teachers randomly assign student pairs to each topic. Throughout these experimentation steps, embedded reflection notes prompt students to generate hypotheses, gather evidence, draw conclusions, and make connections between new and pre-existing ideas. At the end of the fourth activity, all students participate in an on-line discussion to share their knowledge as a completion of the jigsaw activity and learn about the factor that they did not investigate. In the fifth activity, students use a more complex visualization to learn about how population levels impact greenhouse gas emissions and global warming (see Fig. 4). This visualization includes slider bars that allow students to manipulate the population growth rate and CO_2 emission.

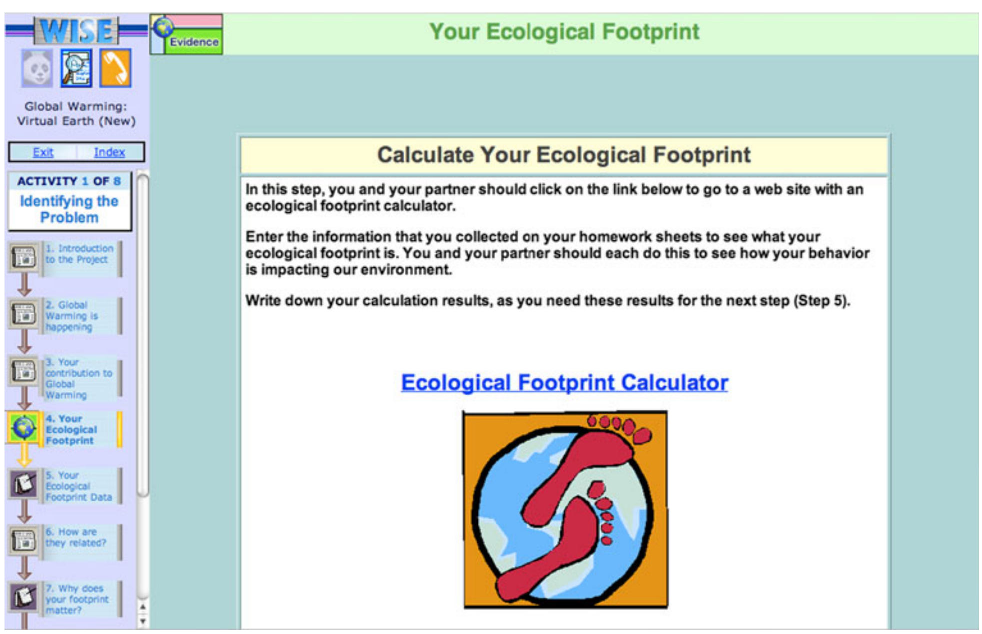

Fig. 1 Screenshot from *Global warming: virtual earth* curriculum unit

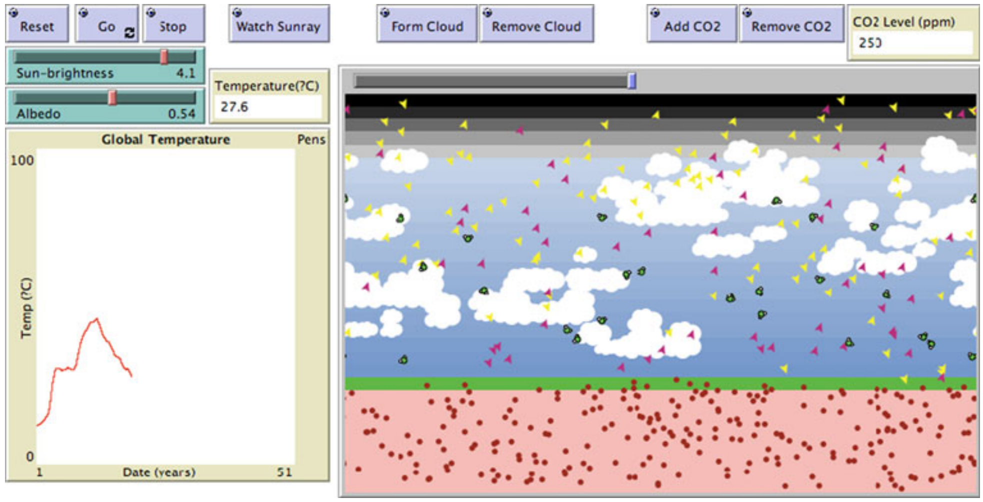

Fig. 2 Screenshot of the greenhouse visualization

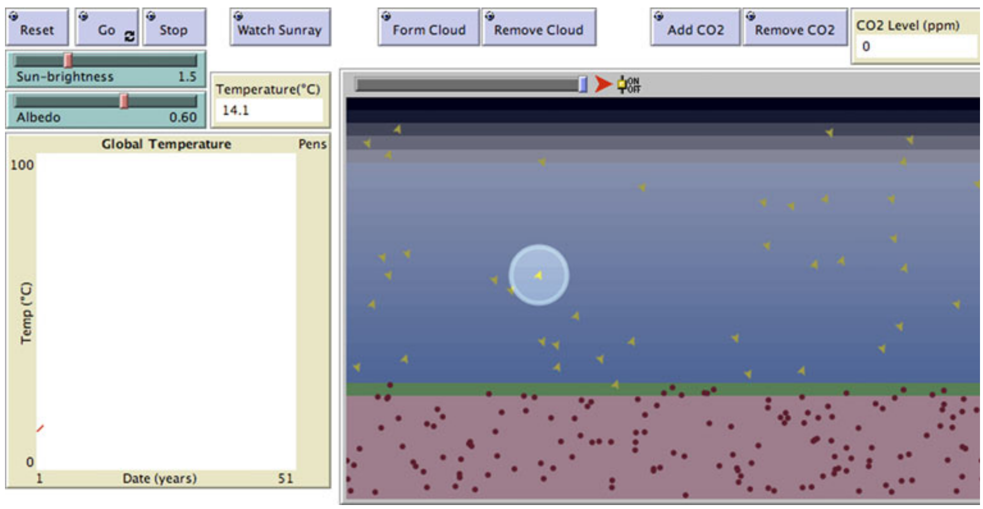

Fig. 3 Screenshot of "watch sunray" feature in the greenhouse visualization

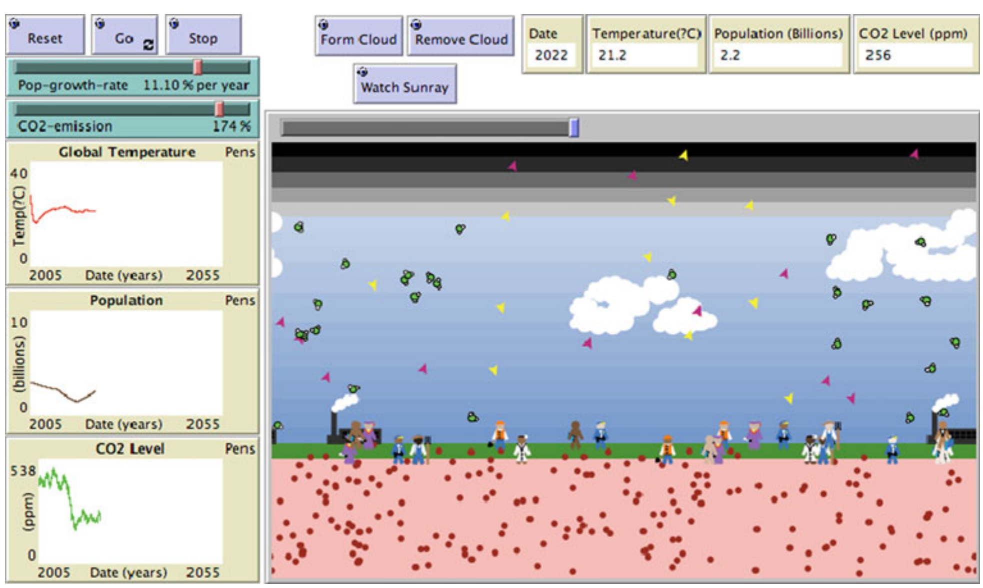

Fig. 4 Screenshot of population growth visualization

In the final activity, students create a family plan to reduce their greenhouse gas emissions and recalculate their ecological footprint based on their planned behavior changes. Table 2 lists the knowledge integration processes that are involved in the various module activities.

The Greenhouse Effect Visualization

The greenhouse visualization embedded in the curriculum unit was created using NetLogo (Tinker 2005). It models processes that occur in the real world phenomenon. In reality, the greenhouse effect is a natural warming process of the earth. As solar energy reaches the Earth, some of it is reflected back to space and some is absorbed into the Earth's surface. The absorbed energy warms the earth's surface, which then emits infrared energy. Some of the infrared energy goes into space. Some is partially trapped by greenhouse gases (such as carbon dioxide). The greenhouse gases absorb and re-emit the infrared energy, radiating it in all directions and thereby warming the earth's surface and atmosphere. Below we describe how the greenhouse effect is illustrated in the visualization.

> Yellow arrowheads stream downward representing solar energy. Some of the solar energy reflects off clouds and more can reflect off the Earth surface.
> If the solar energy is absorbed, it turns into a red dot, representing heat energy. Each dot represents the energy of one yellow solar energy arrowhead. The red dots randomly move around the Earth's interior. The temperature of the Earth is related to the total number of red dots.
> Sometimes the red dots transform into infrared energy (IR) that heads toward space. The probability of a red dot becoming IR depends on the Earth's temperature. When the Earth is cold, few red dots transform to IR energy; when it is hot, most do. The IR energy is represented by a magenta arrowhead. Each carries the same energy as a yellow arrowhead and as a red dot. The IR light goes through clouds but can bounce off CO_2 molecules (Tinker 2005).

See Fig. 2 for a screenshot of the visualization. To conduct experiments with the visualization, students begin by clicking the "reset", then "go" buttons. The incoming solar energy value is set at 1.0 to correspond to our sun. The beginning setting for Albedo is 0.6 are to approximate the current conditions on Earth. The Albedo slider controls how much solar energy hitting the Earth is absorbed. If the Albedo is 1.0, the Earth *reflects* all sunlight. This could happen if the Earth froze and is indicated by a white surface. If the Albedo is zero, the Earth *absorbs* all sunlight. This is indicated as a black surface. Students can vary the amount of incoming solar energy, and the Albedo level of the Earth's surface by moving slider bars.

In the visualization, greenhouse gases are represented as CO_2 molecules. Carbon dioxide blocks infrared energy, but not solar energy. Students manipulate greenhouse gases by clicking a button labeled "add CO_2". Each time they click the button, 25 ppm of CO_2 is added to the atmosphere. They can decrease atmospheric CO_2 by clicking another button labeled "remove CO_2". This subtracts 25 ppm per click. Students can add up to 150 ppm.

Students can add and remove clouds by clicking on buttons labeled "add clouds" and "remove clouds". In this visualization, clouds block solar energy, but not infrared energy.

Students can manipulate the variables while the visualization is in motion. However, in order to conduct experiments, students are instructed to set up the conditions then click "go". They are asked to click "stop" once they have observed the visualization and the temperature change, then reset the parameters and run the visualization again.

The instructions tell students that they should manipulate only the target variable and not make any other changes in the visualization interface. This type of direct instruction is designed to provide guided experimentation support to help students conduct valid scientific investigations that are more likely to lead to normative scientific ideas (Klahr and Nigam 2004). The instructions also remind students they can conduct as many experiments as they want to. Embedded notes ask students to explain the

Table 2 Knowledge integration processes and module activities

	WISE activity	Knowledge integration process
1	Introduction	Eliciting ideas/introducing new ideas
2	The earth's energy balance	Eliciting ideas/introducing new ideas
3	Conducting experiments about greenhouse gases	Introducing new ideas/developing criteria for sorting ideas
4	(Jigsaw activity) conducting experiments about clouds or albedo	Introducing new ideas/developing criteria for sorting ideas
5	Exploring the population model	Eliciting ideas/introducing new ideas
6	Creating a family plan	Sorting and reorganizing ideas

Multiple knowledge integration processes are involved in each activity. This table lists the primary processes that are included in the activities to clarify the relationship between the module design and knowledge integration role of the variables that they just investigated. They are specifically asked to create their explanations based on the information they gathered in their experiments.

Windows in the visualization show a numerical representation of the concentration of greenhouse gases in the atmosphere, the temperature of the Earth and the Albedo level. Additionally, there is a graph representing the temperature fluctuations that occur as a result of students' manipulations (Tinker 2005).

Procedure

Students' participation began with their individual completion of an eight-question, paper-and-pencil pre-test. Classroom teachers administered the pre-tests during the students' normal class meetings. The questions, presented in Table 3, were primarily open-ended questions about global warming, the greenhouse effect, and the individual factors that contribute to these phenomena.

Following the pre-test, all students worked in pairs to complete the activities and embedded reflection notes in the *Global Warming: Virtual Earth* curriculum unit. Students participated in the unit activities for five 1-h class periods in 1 week. The curriculum unit was enacted as a part of the teachers' normal classroom instruction. The teacher served as the lead instructor. At least one researcher was present in the classrooms to observe the enactment and to assist with technology issues. Following the unit activities, students individually completed a paper-and-pencil post-test comprising the same questions included in the pre-test. The pre- and post-assessments lasted approximately 20 min each.

Data Analysis

The main data were generated from students' responses to eight open-ended questions included in the pre-post tests. The first three questions assess students' understanding of the target phenomena (the greenhouse effect and global warming) at a systemic level. Questions one and two ask students to describe the greenhouse effect and global warming. Question three asks them to describe the difference between the two.

Question four assesses students' alternative ideas about the factors that contribute to global warming. It includes a checklist of eight factors that are possible contributors. Students were asked to "Look at the list below and select all of the factors that you think have an effect on global warming." Students received a score of 1 through 6 based on the number of correct selections.

Questions five, six and seven ask students to explain how particular components (Albedo, clouds, and greenhouse gases) are involved in the greenhouse effect. The final question is a representation analysis prompt. It asks students to analyze how an actual greenhouse represents the scientific phenomenon, the greenhouse effect.

Students' responses on all questions except number 4 were coded using knowledge integration scoring rubrics. Each response received a score of zero through five based on the correctness of the expressed ideas and links between the ideas. Each rubric was created based on an analysis of the links present in a fully correct response to each question. The first author generated an initial rubric that listed the correct response and example partially correct responses for each level of scoring.

A group of researchers familiar with the curriculum unit design and the knowledge integration framework reviewed the rubric and the example responses to ensure that the correct criteria would be applied to the data. Twenty percent of the tests were coded by a second researcher for reliability (97%). Discrepant codes were resolved via discussions between the coders.

One of the pre/post test questions was, "Describe how the greenhouse effect happens. Try to make sure that you use the following three terms: (1) solar energy, (2) infrared energy and (3) greenhouse gases." A complete, well-integrated response includes linked information about solar energy, infrared energy, greenhouse gases, and the Earth's temperature. The first three columns in Table 4 show the general sequence of scores and knowledge integration levels that are used to code students' responses to each of the open-ended pre/post questions. This framework is used across all of the pre/post questions except question #4. The fourth column lists example question one responses for each KI level.

Matched t-test analyses were conducted to measure differences in students' understanding prior to and following their participation in the unit activities. For each t-test, Cohen's d was calculated to report the effect sizes (Cohen 1992). These data help show how participating in the interactive unit activities changed students' understanding of the greenhouse effect and global warming.

Results

Changes in Understanding

Following participation in the *Global Warming: Virtual Earth* curriculum unit activities, students' ideas were more normative and better integrated. Scores from each question were summed to calculate an overall learning score. Mean overall learning scores improved from pre to post participation (t (189) = 8.66, $p < .001$).

Responses to individual pre-post test questions were analyzed using matched t-tests for a more detailed

Table 3 Pre-post test questions

1. Describe how the greenhouse effect happens. Try to make sure that you use the following three terms: (1) solar energy, (2) infrared energy (IR), and (3) greenhouse gases.
2. What is global warming?
3. What is the difference between the greenhouse effect and global warming?
4. Look at the list below and select all of the factors that you think have an effect on global warming. You can select more than one.

   ____ Acid Rain
   ____ Water Vapor
   ____ Greenhouse Gases
   ____ Clouds
   ____ Carbon Dioxide
   ____ The Ozone Layer
   ____ Solar Energy
   ____ Infrared Energy
5. What is the role of albedo in the greenhouse effect?
6. What is the role of clouds in the greenhouse effect?
7. What is the role of greenhouse gases in global warming? Be sure to be as detailed as possible when you explain your answer. You can draw a picture to help explain your thoughts.
8.

A

B

Picture "A" shows a real greenhouse where light form the sun passes through the glass panels and heats the inside. The glass panels of the greenhouse keep the heat energy from escaping.

Picture "B" shows the greenhouse effect that happens on Earth. Which part of the picture is like the glass of the greenhouse? **Circle One.**

SUN SPACE ATMOSPHERE EARTH

Explain your answer.

examination of changes in students' understanding. See Table 5 for a summary of the analyses.

The first three questions address students' systemic understanding of the greenhouse effect and global warming. Systemic refers to their global understanding of the phenomena.

The "greenhouse" question asked students to explain how the greenhouse effect happens. The question also

Table 4 Example knowledge integration (KI) rubric and example student responses to question #1, "describe how the greenhouse effect happens"

Score	KI level	Description	Example student response
0	No answer	Blank	
1	Irrelevant	Students write some text, but do not answer the question asked	I don't know what a greenhouse is.
2	Incorrect	Response is scientifically incorrect	The greenhouse gases come out from the greenhouse and into the atmosphere, which creates the greenhouse effect
3	Partial link	Students have relevant and correct ideas, but do not fully elaborate lings between them in a given context	The greenhouse gases keep the IR in
4	Full link	Students elaborate a scientifically valid link between two ideas relevant to a given context	Too much CO2 builds up, making the infrared energy bounce back down to the Earth and so the temperature gets higher
5	Complex link	Students elaborate three or more scientifically valid links among ideas relevant to a given context	Sunlight heats the Earth causing it to release IR energy which then bounces off a greenhouse gas such as CO2, back towards the Earth. This warms the overall temperature

Try to make sure that you use the following three terms: (1) solar energy, (2) infrared energy (IR), and (3) greenhouse gases"

Table 5 Pre-post test performance analyses

	Pre-test Mean (SD)	Post-test Mean (SD)	Difference Mean (SD)	Effect Size (d)	*t*	*p*
Item 1—Greenhouse effect	1.87 (1.10)	2.73 (1.19)	.86 (1.37)	.63	8.66	.001
Item 2—Global warming	2.38 (.87)	2.91 (.97)	.53 (1.04)	.50	6.96	.001
Item 3—Difference	1.73 (1.06)	2.75 (1.07)	1.02 (1.47)	.69	9.52	.001
Item 4—Alternative ideas	2.43 (1.67)	3.22 (2.08)	.79 (1.68)	.47	6.47	.001
Item 5—Albedo	.74 (.76)	1.64 (1.30)	.90 (1.45)	.62	8.54	.001
Item 6—Clouds	1.27 (1.00)	2.24 (1.23)	.97 (1.46)	.66	9.24	.001
Item 7—Greenhouse gases	1.65 (1.23)	2.46 (1.29)	.81 (1.48)	.55	7.56	.001
Item 8—Atmosphere	2.25 (1.91)	2.52 (1.19)	.27 (1.39)	.19	2.65	.001
Total KI score	17.85 (5.41)	24.36 (6.09)	6.51 (6.45)	1.01	9.32	.001

stated that students should be sure to mention three key factors: solar energy, infrared energy, and greenhouse gases. A systemic understanding of the greenhouse effect should allow individuals to explain that solar energy enters the Earth's atmosphere, the transformation of solar energy to infrared energy, the Earth's emission of infrared energy, and the greenhouse gases' ability to "trap" infrared energy in the Earth's atmosphere.[1] Responses were coded using the knowledge integration (KI) rubric in Table 2. Students' performance on the post-test showed improved understanding of the greenhouse effect (t (189) = 6.96, $p < .001$).

Prior to instruction, students had some understanding of the greenhouse effect, but it was generally incomplete or incorrect. For example, one student wrote, "*I think the greenhouse effect happens when solar energy is trapped in the stratosphere*", and another wrote, "*The solar energy gets stronger and the IR goes away*." Several responded with "*I don't know.*" On the post-test, students' responses included more ideas about the interaction of the key factors. They also had more links between their ideas indicating that their understanding was more integrated. A representative post-test response is, "*I think the solar energy from the sun gets soaked in by the Earth. Then the Earth gives off infrared energy. The energy is trapped by the greenhouse gases, creating the Greenhouse Effect.*"

The "global warming" question simply asked, "What is global warming?" Prior to instruction, students responded to this question with incomplete ideas from popular media or ideas related to other units of study in their classes (i.e.,

[1] We recognize that using the term *trap* could lead to incorrect assumptions about how greenhouse gases and infrared energy interact. The actual process entails the greenhouse gases absorbing and re-emitting infrared energy into the atmosphere. In our discussions with students and teachers, we referred to this as an *interaction* between the greenhouse gases and infrared energy. As teachers and researchers presented the visualization, they pointed out the limitations of scientific models and discussed the visualization as a scientific model that seemed to show greenhouse gases making the infrared energy *bounce back* but that the actual process involved absorption and re-emission.

weather or pollution). In several responses, students also included ideas about the effects of global warming rather than a description of the phenomenon. Some example responses are, "*It's when the sun's so hot, it makes the North and South Pole melt and flood the world.*" and "*It's when the ozone layer gets thinner*". After participating in the module, more students provided more responses focusing on the relationship between the greenhouse gas levels and the earth's temperature such as, *"Too many greenhouse gases make the earth hotter."* and "*Too many greenhouse gases trap the IR and the earth gets too hot"*. Their responses indicate more normative scientific knowledge (first example) and more integrated ideas (second example) (t (189) = 6.96, $p < .001$).

On the pre-test, two commonly expressed responses to the question asking students to explain the difference between the greenhouse effect and global warming were, *"They are the same thing."* and *"The greenhouse effect causes global warming."* On the post-test, students showed that they understood that these two were different phenomena, and they were able to generate integrated explanations describing the difference (t (189) = 9.52, $p < .001$). This finding is presented in greater detail in our discussion of students' alternative ideas.

Three questions asked students to explain the roles of individual contributing factors (clouds, Albedo, and greenhouse gases) in the greenhouse effect. During instruction, students conducted virtual experiments to learn about each of these factors using the greenhouse visualization. Findings show that students' understanding for each of the factors improved following their participation in the curriculum unit. Knowledge integration scores for each prompt were submitted to matched t-test analyses. The results show differences between pre and post test scores for each item (Albedo—(t (189) = 8.58, $p < .001$); Clouds—(t (189) = 9.24, $p < .001$), Greenhouse gases—(t (189) = 7.57, $p < .001$). Table 6 lists examples of students' responses to each of these prompts on the pre- and post-test assessments.

Combined, these data show that students improved their knowledge of individual concepts and that improve their understanding of the greenhouse effect and global warming phenomena.

Alternative Ideas

To measure how participating in the unit impacted students' alternative ideas, one item asked students to select the factors that have an effect on global warming. The list included correct and incorrect items. See Table 3. Students received one point for each correct item selected. Mean scores were submitted to a matched t-test analysis. The results show that students selected more correct items on the post-test (t (189) = 6.49, $p < .001$).

Discussion

Overall, students show increased understanding of the target phenomena, but there is room for growth. Using the knowledge integration framework to code their responses to the open-ended questions allows us to see improvements in their knowledge and movement toward more normative, integrated understanding. Students were able to explain how the greenhouse effect happens and include the role of greenhouse gases, solar energy, and infrared energy in their responses. They could also explain the difference between the greenhouse effect and global warming. Their

Table 6 Representative student responses to pre-post test componential questions

Pre-post question	Pre-test responses	Post-test responses
What is the role of Albedo in the greenhouse effect?	I don't know. (1)	Albedo bounces off sunlight (3)
	I haven't studied the greenhouse effect. (1)	Albedo is the ability of a surface to reflect light. Open water absorbs heat while white ice and snow reflect it. (4)
	I don't know what Albedo is. (1)	
What is the role of clouds in the greenhouse effect?	To cool off the solar energy. (2)	Clouds in the greenhouse effect make the earth's temperature cooler. (3)
	Clouds make rain. (2)	Clouds help solar energy go away by a little (3)
	It makes a mist. (2)	They help cool down the earth and reflect some of the solar energy. (4)
What is the role of greenhouse gases in global warming?	I think the greenhouse gases contaminate the air. (2)	Greenhouse gases reflect the heat causing a steady rise of temperature. (4)
	I think the greenhouse gases make the air polluted. (2)	The role of greenhouse gases in global warming is to make the produced IR bounce back to Earth to heat it up (4)
	The gasses make it humid and really wet and hot. (2)	

performance on these questions indicates that they are developing an integrated understanding of these phenomena.

In order to develop a deeper understanding of the greenhouse effect and global warming, students had to learn about the individual components (solar energy, infrared energy, greenhouse gases, etc.), and understand the relationships between them. Two of the main relationships among the individual components highlighted in the unit are that higher albedo levels indicate a higher level of reflectivity from the Earth's surface leading to increased reflection of solar energy, less IR emission, and lower temperatures, and that greenhouse gases reflect infrared energy back to the Earth's surface, causing the Earth's temperature to increase. Some students developed an understanding of the relationship between greenhouse gases, infrared energy and the Earth's temperature. Very few understood the relationship between albedo and the Earth's temperature.

Prior to instruction, students' knowledge consisted mainly of causes of global warming and results of the global warming phenomenon. They did not fully understand the scientific interactions and underlying principles that describe how the greenhouse effect and global warming occurs. In this study, in order for students to receive credit as having an integrated understanding of a target concept or phenomenon, their responses must have correct, *interconnected* ideas. For example, students could generate responses explaining the greenhouse effect by mentioning all of the individual components required for a correct response (solar energy, infrared energy, greenhouse gases) but have incorrect links among the components (solar energy (rather than infrared energy) is trapped by greenhouse gases). Knowledge integration scoring accounts for incremental changes by identifying levels of understanding based on ideas *and* links between ideas. While there is certainly room for growth, students do show that they learned more about the components involved in the greenhouse effect.

Changes in students' understanding observed in this study are similar to children's understanding of the Earth as discussed in Vosniadou and Brewer's (1992, 1994) work. They found that children have a variety of mental models of the physical word (i.e., the shape of the Earth, the day/night cycle) that are based on their everyday experiences. Once they acquire new information they modify their ideas to be more scientifically valid. In their work on children's knowledge of the Earth, Vosniadou and Brewer identify intermediate mental models that represent children's attempts to reconcile new knowledge that the earth is a sphere with their preexisting knowledge that the earth is flat. Some students reconcile the competing ideas by holding a dual earth mental model; that there is one flat earth (that they understand) and another spherical earth (to the scientifically accepted model). Others attempted to revise their initial models by generating a model that combines new ideas with old ones. An example is the hollow sphere model that has a flat ground surface for people to live on inside a hollow, spherical earth.

In our work, students initially understand that greenhouse gases are involved in the global warming and that heat from the sun warms the Earth. Their post-test responses show that they learn that greenhouse gases "trap" energy to warm the Earth's surface. Most fail to understand that the greenhouse gases trap infrared energy rather than solar energy. Although we do not see evidence of a complete, integrated understanding of the greenhouse effect and global warming for all students, we do see evidence that they are revising their knowledge. This is consistent with Vosniadou and Brewer's conceptual change theory that describes conceptual change as a gradual, continuous process. As they reconcile new ideas with their pre-existing knowledge, students have generated an intermediate representation of the greenhouse effect that includes correct and incorrect ideas.

The primary learning experiences for learning about the factors involved in the greenhouse effect were experimentation activities using the greenhouse virtual experiment. Students needed to conduct valid experiments in order to gain a deep understanding of each factor and develop normative ideas about the greenhouse effect. In efforts to support effective experimentation strategies, the directions that accompanied the visualization were specific and direct. Teachers and the researchers would also move throughout the classroom to monitor students' interactions and try to intervene with reflective questions about their interactions to help them use effective strategies. In this study, we do not have evidence of what kinds of experimentation strategies students used. However, our ongoing work is allowing us to investigate these types of issues. We are collecting log data of students' interactions with the visualization to see not only if they use the controlling variables strategy, but also to characterize what types of strategies they naturally use in their exploration and experimentation. We are also examining the effect of different types of support for experimentation strategies. Our future work includes comparing additional practice designing experiments with critiquing experiments. We will also compare the impact of direct instruction about the experimental process versus direct instruction on the scientific content of the unit.

As mentioned earlier, students had trouble understanding the transformation of solar energy to heat energy to infrared energy. This meant that many post-test responses were incorrect because students thought that *solar* energy rather than *infrared* energy was being reflected back to the

Earth's surface by CO_2. A follow-up study expanded the prompt in question #1 to include a drawing option such that, students are asked to draw and label a picture of how the greenhouse effect happens. Future studies will examine students' drawings and explanations to measure their understanding of the energy transformation that is key to a deep understanding of this complex phenomenon.

Finally future work with this curriculum unit will involve a series of studies focusing on the affordances of the greenhouse visualization. Our current findings indicate that students' participation in the curriculum unit activities as a whole increases their understanding. We would like to know more about how their interactions with the visualization in particular impacts learning outcomes.

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