International Journal of Science Education
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tsed20

A Design-based Approach to Fostering Understanding of Global Climate Change

Vanessa Svihla [a] [b] & Marcia C. Linn [b]

[a] Teacher Education, University of New Mexico, Albuquerque, NM, USA

[b] Graduate School of Education, University of California, Berkeley, Berkeley, CA, USA

Available online: 29 Jul 2011

To cite this article: Vanessa Svihla & Marcia C. Linn (2011): A Design-based Approach to Fostering Understanding of Global Climate Change, International Journal of Science Education, DOI:10.1080/09500693.2011.597453

To link to this article: http://dx.doi.org/10.1080/09500693.2011.597453

International Journal of Science Education
2011, 1–26, iFirst Article

RESEARCH PAPER

A Design-based Approach to Fostering Understanding of Global Climate Change

Vanessa Svihla[a,b*] and Marcia C. Linn[b]
[a]*Teacher Education, University of New Mexico, Albuquerque, NM, USA;* [b]*Graduate School of Education, University of California, Berkeley, Berkeley, CA, USA*

To prepare students to make informed decisions and gain coherent understanding about global climate change, we tested and refined a middle school inquiry unit that featured interactive visualizations. Based on evidence from student pre-test responses, we increased emphasis on energy transfer and transformation. The first iteration improved comprehension of the visualizations resulting in better understanding of energy transfer ($n = 67$). The second iteration improved understanding of energy transformation ($n = 109$) by adding pivotal cases, reducing deceptive clarity, and emphasizing distinguishing of ideas. Focusing student investigations in the second version allowed students to make more normative, personally relevant decisions related to their energy use. These iterative refinements reflected knowledge integration principles and offer guidance for designers of inquiry units.

Keywords: *Learning environment; Environmental education; Visualization*

Introduction

Global climate change is a particularly challenging topic for students, both because of the mixed messages from popular media and because it involves complex systems (e.g., Cordero, Marie Todd, & Abellera, 2008; Liu & Hmelo-Silver, 2009; Mohan, Chen, & Anderson, 2009). To prepare students to weigh new arguments and make informed decisions, we designed instruction to promote coherent understanding of mechanisms and contributing factors. We leveraged students' everyday ideas, made global climate change personally relevant, and used visualizations to help students

*Corresponding author: Graduate School of Education, University of California, Berkeley, Tolman Hall, mc1670, Berkeley 94720, USA. Email: vsvihla@unm.edu

ISSN 0950-0693 (print)/ISSN 1464-5289 (online)/11/000001–26

DOI: 10.1080/09500693.2011.597453

connect unobservable processes and variables (such as heat transfer and green house gases in the atmosphere) to observable phenomena (such as albedo, the reflectivity of a surface). Students interacted with the visualizations to gain understanding of the impact of their everyday activities on climate change. We investigated three research questions:

- How can we design instruction featuring interactive visualizations to help students gain coherent ideas about global climate change?
- How can inquiry instruction guide students to improve their ideas about energy transfer and transformation?
- How can we structure experimentation about global climate change to impact personal decision-making?

Climate Change and Energy

We distinguish *global climate change, global warming, and the greenhouse effect. Global climate change* refers to the future, present, and paleoclimate warming and cooling trends of either natural or anthropogenic cause. *Global warming* refers to increasing average global temperature. Global warming has occurred multiple times over Earth's history, and is believed by most of the scientific community to be occurring currently. *The greenhouse effect* is the predominant mechanism for global warming (changes in solar intensity being another) and is an important natural process that creates a habitable environment for life on the Earth.

To understand how the greenhouse effect occurs, an understanding of *energy transformation* is important. Greenhouse gases in our atmosphere allow solar radiation to both enter and leave our atmosphere. When solar radiation is absorbed by the Earth, it transforms into thermal energy. When it is re-emitted by the Earth into the atmosphere, it transforms again into infrared radiation, which we feel as thermal energy. The greenhouse effect occurs when greenhouse gases prevent infrared radiation from leaving the atmosphere. A coherent understanding of global climate change includes knowing that it is the *transformed energy* that cannot get out of the atmosphere. Students need to distinguish this view from their frequently held view that global warming occurs when the ozone hole lets more solar radiation in (e.g., Andersson & Wallin, 2000).

From the perspective of human experience (but not geological history), global climate appears stable, and furthermore, changes seem small compared with changes associated with seasons and weather. However, over the past 200 years, human activity has slowly but cumulatively increased the concentration of greenhouse gases in the atmosphere, allowing less infrared radiation to escape from the atmosphere, leading to global warming. Small changes in the global energy balance can significantly change the global temperature. For example, in the Early Devonian period (416 million years ago), the carbon dioxide concentration in the atmosphere was estimated to be 600 ppm higher than current concentrations (Le Quéré, Raupach, Canadell, & Marland, 2009; Simon & Goddéris, 2007). This corresponds to more infrared radiation trapped in the atmosphere. Global temperatures for the Devonian period are estimated to have been 15°C warmer than today (Joachimski et al., 2009). Such temperatures melt land ice, and over time, cause thermal expansion of the oceans. In the Devonian period, this resulted in shallow oceans covering much of the land (Joachimski et al., 2009). A return to conditions like those in the Devonian period would not support the agriculture needed for the current human population.

Global Climate Change Curriculum

To investigate the research questions, we refined a Web-based Inquiry Science Environment (Slotta & Linn, 2009) unit called Global Warming (WISE, Figure 1). The unit incorporated NetLogo visualizations (Wilensky & Reisman, 2006) created by the Concord Consortium representing the Earth and the atmosphere. Students explored albedo, carbon dioxide emissions, population, and pollution as factors leading to climate change (Varma, 2008). Students made significant gains in understanding the greenhouse effect using the NetLogo visualizations (Varma, 2010).

The knowledge integration (KI) framework aligned the design of instruction and assessment. Students develop a repertoire of incoherent and fragmented ideas as a result of their experiences. The KI framework emphasizes science learning that requires students to integrate ideas from multiple sources and determine the most fruitful, generative, and coherent perspective. KI principles, based on prior research, guided initial unit design (Linn & Hsi, 2000):

- make the content accessible (e.g., build on student ideas, connect to personally relevant experiences, focus attention on salient information);
- help students learn from each other (e.g. encourage students to compare viewpoints, involve students in debate, support negotiation of meaning);
- make thinking visible (e.g., link multiple representations, model scientific thinking, visually represent data collected by students); and
- promote autonomous lifelong learning (e.g., establish a generalized inquiry process using the inquiry map (Figure 1), include predictions and explanations, encourage reflection on alternatives, support problem finding)

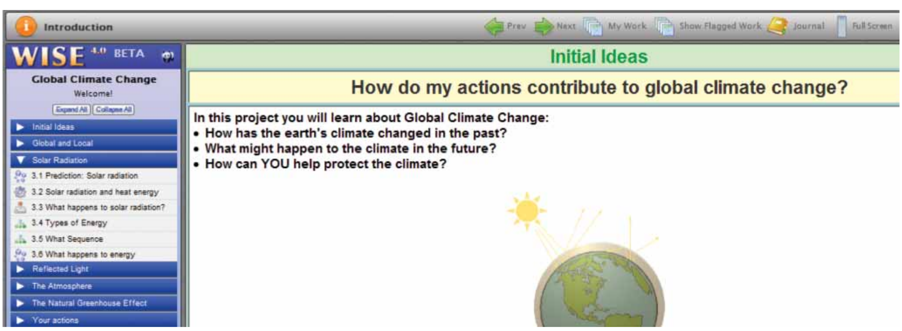


Figure 1. WISE guides students and visually represents the inquiry process

A partnership of teachers, technologists, content experts, and researchers created a new version called Global Climate Change 1 (GCC1). The initial redesign plans were drafted at a retreat where the partners reviewed student work from the Global Warming unit. The partners diagnosed weaknesses in the understanding of energy transfer and transformation.

The AAAS Benchmarks recommend that middle grade students be introduced to energy through energy transformations:

> At this level, students should be introduced to energy primarily through energy transformations. Students should trace where energy comes from (and goes next) in examples that involve several different forms of energy along the way: heat, light, motion of objects, chemical, and elastically distorted materials (American Association for the Advancement of Science, 1993, p. 84).

In California, energy transformations are introduced in elementary school, and revisited in sixth grade as students learn about energy in the Earth system (Curriculum Development and Supplemental Materials Commission, 2003).

The partners created a conceptual design, including a sequence of learning goals, a story board of ways to address the learning goals, and assessments corresponding to the learning activities. The GCC1 version strengthened the role of energy and inquiry in the unit and focused on global climate change. Global Climate Change 2 (GCC2) was created based on findings from the first classroom implementation of GCC1.

Students' Ideas about Global Climate Change

Students' ideas come from everyday experiences, observations, school experiences, and popular media. Middle school students have varied ideas about how greenhouse gases might cause global warming. Many students associate greenhouse gases with global warming. When asked to explain why or how greenhouse gases might cause global warming, students generate many links and connections. For example:

- The sun is made out of gases, and it's the world's source of energy, therefore more gases make it even warmer!
- I think it would make a warmer climate because the coal is burning which is warm so it would make a warm climate.
- It will be warmer because you breath out carbon dioxide. It's warm so if more carbon dioxide increases it will be warmer.

The first example shows how a student might connect school-based ideas to support an assertion, such as *the sun is gaseous* and *the sun is hot*, ergo, *gases are hot*, and also provide additional ideas that *the sun is our energy source*, even if they are not directly related to the question. The other examples incorporate everyday ideas. Implicit in the second example are the ideas that greenhouse gases come from burning coal and that burning is an exothermic process. The latter is grounded in everyday experiences: *burning things are hot.* The third example, here expressed in relation to breathing, but also commonly found associated with car exhaust, is similarly grounded in everyday experiences: *my breath (or car exhaust) feels warmer than the air around it*, and tied to science ideas, *my breath contains* CO_2.

Students may also connect their ideas to settings. When one explanation is applied to everyday setting, and another is applied to school science settings, students may not reconcile their ideas. These examples illustrate the diverse ideas and links that students generate (e.g., that temperature is a property of the material). They illustrate the range, origins, and conflicts in students' repertoires. To help students develop coherent normative ideas, we address the repertoire of ideas students have. We help them distinguish ideas and recognize similarities between everyday and formal settings.

Designing Inquiry Instruction for Coherent Understanding

Extensive research supports the value of inquiry learning (Krajcik, Slotta, McNeill, & Reiser, 2008) and the benefit of using technology to guide students to succeed (e.g., Blumenfeld et al., 1991; Edelson, 2002; Edelson, Gordin, & Pea, 1999; Quintana et al., 2004). Software scaffolds can guide students to engage in specific inquiry activities such as testing ideas and conducting investigations and help students keep track of progress and organize their problem-solving (Collins & Brown, 1988; Davis, 2004).

Research points to specific activities that promote coherent understanding. Various studies have demonstrated the benefits of prompting students to reflect on their learning (Linn & Clancy, 1992; Linn & Eylon, 2011; Scardamalia & Bereiter, 1991) provided the prompts are carefully crafted to support KI (Davis, 2004). Reflection can focus students on integrating their understanding by recognizing patterns (Reiser, 2004; Reiser et al., 2001) or testing their ideas in new contexts. The idea that a test can be a learning event has been demonstrated in laboratory settings (Roediger & Karpicke, 2006). When not encouraged to reflect, students may focus on products rather than KI (Krajcik et al., 1998).

Eliciting students' ideas has proven valuable in collaborative activities and predict-observe-explain sequences (Gunstone & Champagne, 1990). When students generate their ideas, they can test them and get feedback about their views from experiments, collaborators, and teachers. If students do not have an opportunity to generate their own ideas, they may continue to use them in out-of-school contexts.

Allowing students to distinguish their ideas as they investigate scientific phenomena supports the development of integrated understanding (Reiser et al., 2001; Sandoval, 2003; Sandoval & Reiser, 2004). Reiser describes how software tools provide structure and problematize the content (Reiser, 2004). Distinguishing ideas can overcome the deceptive clarity of visualizations that occurs when students overestimate their understanding and fail to explore nuances (Linn, Chang, Chiu, Zhang, & McElhaney, 2010). Carefully structured investigations can focus students' experimentation and yield meaningful results.

Inquiry instruction includes adding new ideas that students can explore. New ideas may be too complex or deceptively clear and hence be ignored. Research shows that pivotal cases can engage students in restructuring non-normative ideas (Chiu & Linn,

2012) by contrasting two conditions, connecting to personally relevant experiences, introducing the language and methods of science, and encouraging learners to capture their ideas in a narrative.

These and other investigations suggest a pattern that promotes integrated understanding (Linn & Eylon, 2011). The KI pattern calls for eliciting ideas so students consider all their ideas during instruction. To improve understanding the KI pattern calls for adding new, carefully designed ideas, such as pivotal cases. To sort out ideas, the KI pattern emphasizes structuring inquiry so that students develop criteria to evaluate and distinguish ideas and avoid deceptive clarity. To consolidate understanding, the KI pattern calls for reflection and autonomous application of ideas to new problems.

Past research that scaffolds learners to follow this pattern has led to gains both in the coherence of content understanding (Linn, Lee, Tinker, Husic, & Chiu, 2006) and in understanding the nature of science (Bell, 2000). It has highlighted opportunities to leverage diverse strategies for learning (Linn, Bell, & Davis, 2004; Linn & Hsi, 2000). The pattern guided the redesign of the Global Warming unit, especially by highlighting the importance of overcoming deceptive clarity, using pivotal cases, and structuring experimentation.

Methods

We tested the two versions of the Global Climate Change unit, GCC1 and GCC2 with a total of three teachers who were part of the partnership design process (Figure 2). GCC1 was revised based on feedback from one teacher and evidence from student interactions and outcomes while using the unit. The first author observed the classes while the curriculum was being used. GCC2 was then tested with three teachers. We investigated learning using embedded assessments, pre-tests, and post-tests. We contrast the gains in KI from GCC1 and GCC2 for the same teacher instructing two different classes.

Participants and Implementation

The participants of this study were sixth-grade students in culturally diverse classrooms in the US taught by three middle school teachers. One teacher taught two consecutive semester-long courses, first using GCC1 ($n = 67$ dyads), then using GCC2 ($n = 65$

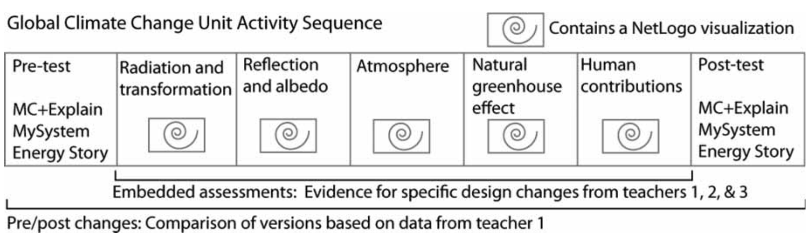


Figure 2. Sequence of activities and assessments in the Global Climate Change Unit

dyads). Teachers 2 and 3 implemented GCC2 ($n = 54$ dyads). Students, aged 11–12 years, attended various elementary schools in the prior year, and therefore had different experience with regard to learning about global climate change. Students completed all work as dyads over the course of 7 days of instruction.

The majority of the time spent during instruction was interacting with WISE on computers. Students generally discussed their ideas with their partners, and it was common practice in all classrooms for partners to take turns controlling the computer. In all cases, the teachers circulated through the classroom while students worked at their desks on laptop computers. Teachers answered questions from individual dyads. They provided written feedback and graded student work.

Each teacher taught with WISE in a slightly different way. Teachers 1 and 2 held brief (less than 7 minutes) whole class discussions when several students had the same question. Teacher two continued an established practice of beginning each class period with a starter (e.g., 'When a volcano erupts, it puts _____________ and ash into the atmosphere') and expecting students to record notes about the starter and the WISE unit in their lab manuals. Teacher three provided worksheets based on selected aspects of the unit for students to take notes. She also asked students to take turns reading passages out of the text book and led discussions based on them.

Assessments and Analysis

To support design decisions, we drew evidence from embedded assessments, pre/post assessments, and log files (Figure 2). We examined computer-generated log files of progress through the unit. These log files provided the sequence and duration of steps visited by a dyad, allowing us to determine whether students revisited steps, which was relevant for making design decisions. Embedded assessments included patterns of predictions, observations of visualizations, and explanations. Written responses to embedded assessments were collected for each dyad, then coded. Initial coding was grounded (Corbin & Strauss, 1990), allowing us to develop KI rubrics, and to identify and track changes in the ideas students recruited from their repertoires to explain scientific phenomena (Tables 1 and 2).

To track student progress, we coded student explanations using the KI rubric (Linn, 2006). The pre and post items include a multiple choice (MC) plus explain question shown to have good validity for measuring KI (Lee & Liu, 2010). This item was coded for KI (Table 1). We compared GCC1 with GCC2 using this common question.

Energy story. As part of the pre- and post-test, dyads completed a constructed-response assessment called an Energy Story (Table 2). Energy Stories allow students to represent their understanding of global climate change in narrative format. They extend typical KI items by asking students to synthesize and explain how energy sources, energy transformation, and energy transfer are involved in a scientific phenomenon, consistent with the goals of pivotal cases. We redesigned the Energy Story between GCC1 and GCC2 and retained the same KI coding scheme (Table 2). This coding scheme was developed specifically to evaluate the energy ideas

Table 1. Assessment item, ideas, and scoring rubric

Multiple choice component		
Burning coal to produce electricity has increased the amount of carbon dioxide in the atmosphere. What possible effect could the increased amount of carbon dioxide have on our planet?		
Choices		*Score*
A warmer climate		2
A cooler climate		1
Lower relative humidity		1
More ozone in the atmosphere		1
Explanation component		*Ideas*
Explain why you chose that answer		Carbon dioxide is a greenhouse gas; greenhouse gases are linked to global warming; greenhouse gases prevent IR from leaving the atmosphere
Score	Level	Description
1	*Irrelevant*	Does not answer the question being asked, or chose not to answer
2	*Non-normative* ideas or links, vague ideas, or scientifically invalid connections between ideas	Other wrong answers: Ascribes warming to ozone being destroyed
3	*Partial link* Unelaborated connections using relevant features OR Scientifically valid connections that are not sufficient to solve the problem	Explains that greenhouse gases, such as carbon dioxide, cause global warming, but no normative mechanism is given
4	*Full link* One scientifically complete and valid connection	Explains that carbon dioxide traps IR in the atmosphere, which leads to a warmer climate
5	*Complex link* Two or more scientifically complete and valid connections	Explains that carbon dioxide reflects IR back to the Earth, and that the IR may be reabsorbed and transformed into heat energy, leading to a warmer climate

students applied to various science contexts. Energy ideas include energy sources, types of energy transfer, and examples of energy transformation (Table 2).

MySystem. To help students track energy transfer and transformation in global climate change, we incorporated a tool called MySystem designed by the Concord Consortium (http://mw.concord.org). MySystem allows students to represent the sequence of energy transfers and transformations by specifying how it left or entered an object (Figure 3). MySystem diagrams were created by dyads as part of the pre- and post-test. The MySystem was identical across GCC1 and GCC2. We compared GCC1 with GCC2 using this common question. MySystem diagrams were coded using dual rubrics developed to capture changes in energy ideas and in systems understanding (Table 3).

Table 2. Knowledge Integration rubric for scoring energy stories

GCCI		GCC2
Write a story to explain how BOTH: (1) energy from the Sun and (2) things people do contribute to global climate change. Include: • Where energy comes from • How energy moves • Where energy goes • How energy changes		Write a story to explain how the Earth is warmed by energy. Include: • Where energy comes from • How energy moves • Where energy goes • How energy changes/transforms
KI Score	Level	Description
1	*Irrelevant*	Does not answer the question being asked, or chose not to answer
2	*Non-normative* ideas or links, vague ideas, or scientifically invalid connections between ideas	Energy comes from the Earth's core
3	*Partial link* Unelaborated connections using relevant features OR Scientifically valid connections that are not sufficient to solve the problem	Includes correct energy source and destination *(Energy comes from the Sun and goes to the Earth)* but does not adequately explain the mode of energy transfer or the role of energy transformation
4	*Full link* One scientifically complete and valid connection	*Includes correct energy source destination (Energy comes from the Sun and goes to the Earth)* and explains ONE of the following: the mode of energy transfer *(by radiation through space)* OR the role of energy transformation *(light energy changes into heat energy then IR)*
5	*Complex link* Two or more scientifically complete and valid connections	*Includes correct energy source destination (Energy comes from the Sun and goes to the Earth)* and explains the mode of energy transfer *(by radiation through space)* and the role of energy transformation *(light energy changes into heat energy then IR)*

Iterative Refinement Results

We iteratively refined the curriculum to help students use visualizations to understand energy in global climate change. We made evidence-based design decisions to strengthen the visualizations of albedo and atmosphere, to improve understanding of energy transformations, and to structure experimentation to make decisions about everyday actions guided by the KI framework.

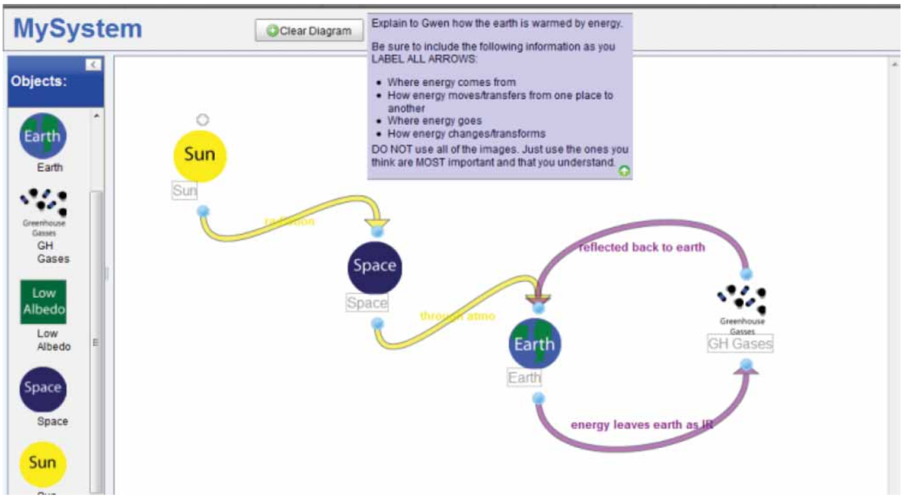


Figure 3. MySystem tool to facilitate students in developing and representing their understanding of energy transfer and transformation in the climate system

Table 3. KI rubrics for MySystem diagrams

	KI coding of energy ideas	KI coding of systems understanding
1	*Irrelevant*	
	No energy ideas present	No links between icons
2	*Non-normative*	
	Represent connections with concepts other than energy (The sun is in space)	Links showing transfer of energy into the Earth–Atmosphere system
3	*Partial link*	
	Vague ideas about energy in general (Energy flows to the Earth)	Links showing transfer of energy into the Earth–Atmosphere system, with some energy reflected
4	*Full link*	
	Normative ideas about energy transfer including accurate understanding of when each form of energy can transfer (Energy from the sun goes through space by radiation)	Links showing transfer of energy into and out of the Earth–Atmosphere system
5	*Complex link*	
	Normative ideas about energy transfer and transformation (Solar radiation is transformed into heat energy when absorbed by Earth)	Links showing transfer of energy into the Earth–Atmosphere system plus a feedback loop

Improving Comprehensibility of the Visualizations

In GCC1, we structured interactions around the NetLogo visualizations highlighting contributions of atmosphere and albedo to global climate change (Figure 4). These interactive visualizations allowed students to manipulate variables and observe the consequences on climate change. Based on evidence from student assessments, we

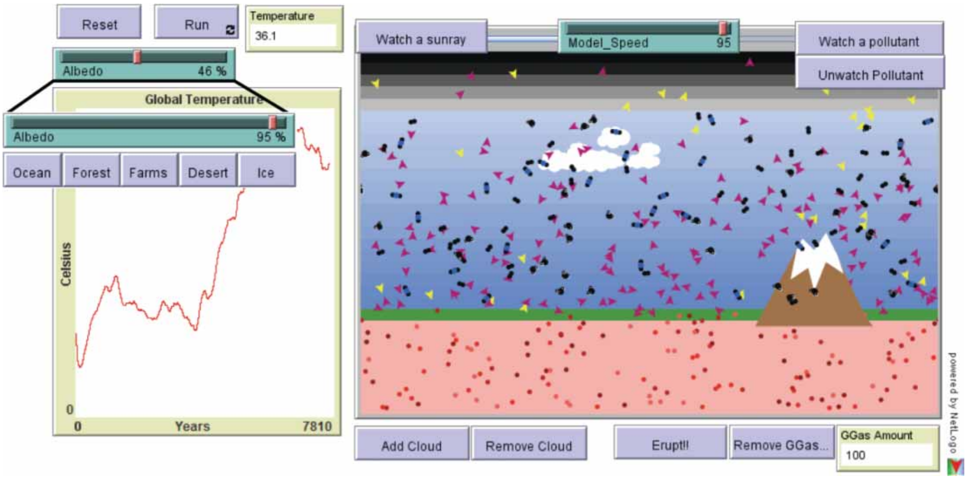


Figure 4. A NetLogo visualization in which students can observe how energy is transformed and interacts with greenhouse gases, clouds, and albedo (surface reflectivity). Albedo is enlarged to show one of the changes made to the visualizations

refined the instruction to improve comprehensibility, add pivotal cases, structure activities to support distinguishing ideas, and reduce deceptive clarity.

Although most students could interpret the NetLogo visualizations in GCC1, approximately 10% of students explained them literally. When asked, ‘Based on your observations, what happens to energy from the sun (solar radiation) when it reaches the Earth?’ students might explain, ‘when the arrow hit the ground it turns out to little red dots. Then when they come out they turn to little arrow again, but the arrows are purple and red.’ This indicated the need to further scaffold students in making connections between the representations (e.g., yellow arrows, red circles) in the NetLogo and the represented concepts (e.g., solar radiation and thermal energy).

To improve comprehensibility, we introduced annotated screenshots of the NetLogo visualizations (Figure 5). The annotations explained the types of energy transfer and energy transformations. We provided feedback on the accuracy of the mapping between the type of energy and the way energy was represented in the visualization.

For the GCC2 version, we found no instances of literal interpretation of the visualizations. In addition, classroom observations and log files of student activity showed that only 20% of the students used trial and error while 80% used the NetLogo visualization or annotated screenshot to determine how energy was being represented. Furthermore, when explaining a model, students used the energy-related terms (e.g., ‘energy from the sun goes into the Earth and changes into heat energy’).

Understanding Energy Transformation: A pivotal case

For GCC1, we designed NetLogo models that allowed students to investigate the role of energy transformations in global climate processes, specifically, from solar radiation

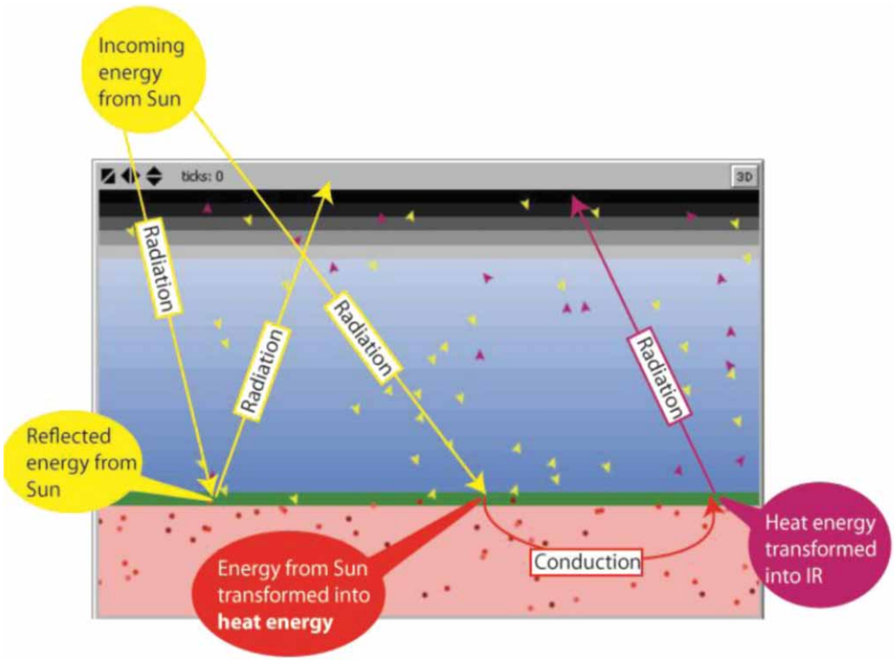


Figure 5. Supporting student understanding of visualizations

to thermal energy, from thermal energy to infrared radiation, and from infrared radiation to thermal energy. Understanding this series of transformations is crucial to forming a mechanistic understanding of climate change. Students need to distinguish infrared radiation from solar radiation. Infrared radiation is reflected back towards the Earth by greenhouse gases, increasing the global temperature. The prompts surrounding the NetLogo visualizations were intended to focus students' attention on the energy but analysis of student responses revealed that across assessments, few students indicated energy transformations.

To improve understanding of energy transformations in GCC2, we added a pivotal case involving watching a sunray so that students could isolate the energy transformations (Figure 6). Students could compare the situation in which the solar radiation was transformed into thermal energy to the situation in which the solar radiation was reflected. Inquiry prompts asked students to explain what happened to solar radiation, and how that related to changes in global temperature. This pivotal case highlighted reflection and transformation and helped students apply their ideas about the importance of energy in global climate change into narratives. Embedded assessments in GCC2 captured student progress in understanding energy transformations.

Understanding Albedo: Improve comprehensibility

Albedo—the reflectivity of a surface—is an important factor in global climate change. An increase in temperature may melt ice-covered land, shifting from high to low

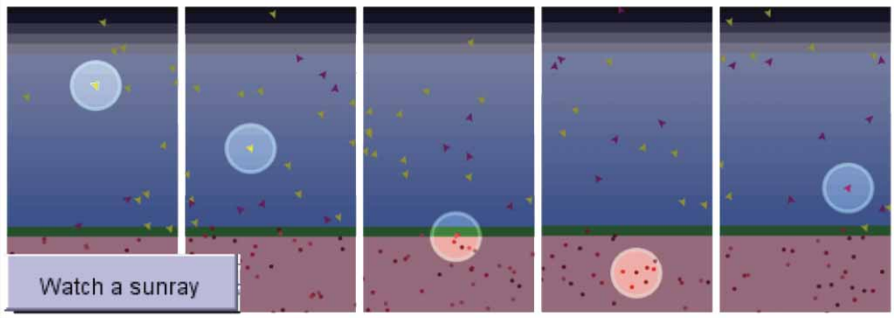


Figure 6. A sequence of screenshots showing the 'Watch a sunray' function to support coherent understanding of energy transformations

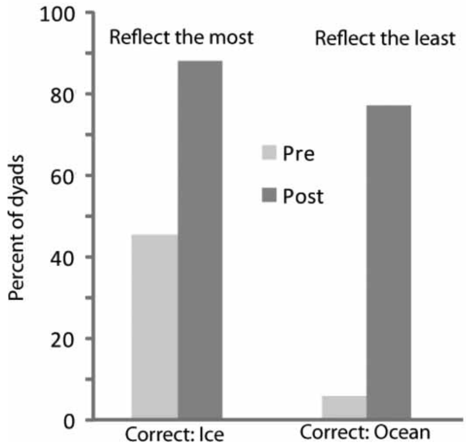
albedo. This in turn means that temperature may increase because more energy is absorbed. Teachers who used a NetLogo visualization in the previous Global Warming unit reported that albedo was a confusing concept for students; in that unit, albedo could be modified by moving a slider along a bar ranging from zero to one, thus changing the color of the land surface in the NetLogo visualization. In GCC1, to improve comprehensibility and allow students to make comparisons that resemble pivotal cases, we connected albedo to familiar settings (Figure 4). Students could compare the effect of oceans, forest, farm, desert, and ice to understand albedo. The teachers reported that connecting the results to familiar settings improved outcomes. One teacher explained,

> I can't even imagine trying to do this unit without [the familiar settings]. They would get nothing out of this unit because it just- ALBEDO? You know? Talking about stuff like that would go right over their head, but with the visualization, the models, that they've done and the fact that they can manipulate them and show different things, different levels of albedo, it's just fantastic.

Another teacher reflected on her own learning as a result of connecting the albedo to familiar surfaces,

> I think the thing that's surprised me most is I hadn't thought about the oceans being low albedo. I had always thought of them as being high albedo because they reflect the sunlight but they also absorb a lot, so that was a good learning for me, that really was. It was fun. I think the environments [for albedo] were very helpful because that makes more sense to them. The kids get environments more than they get a slider. They really do!

To test comprehensibility of the albedo visualization, we compared the prediction choices students made before using the NetLogo visualization to their choices afterward. Since there was no significant difference across teachers or across GCC1 and GCC2, we analyze data for this question across both iterations and all teachers ($n = 84$ dyads). Dyads were significantly more likely to select the environment that reflects the most light (ice) after interacting with the visualization ($Mdn = 2$) than before ($Mdn = 1$, $Z = -5.28$, $p < 0.001$, $r = 0.45$) and significantly more likely to select the environment that reflects the least light (ocean) after interacting with the visualization ($Mdn = 2$) than before ($Mdn = 1$, $Z = -7.62$, $p < 0.001$, $r = 0.72$), Which surface-- Ocean, Forest, Farm, Ice, or Desert would reflect the most solar radiation? The least?



	Frequencies	N
Surface reflects most	Negative Differences [a]	4
	Positive Differences [b]	40
	Ties [c]	40
	Total	84
Surface reflects least	Negative Differences [a]	0
	Positive Differences [b]	64
	Ties [c]	24
	Total	84

[a] Pre>Post
[b] Pre<Post
[c] Pre=Post

Figure 7. Percent of dyads correctly identifying surfaces that reflect or absorb solar radiation before and after interacting with the NetLogo visualization on albedo. Frequencies of sign changes of predictions to post-observation choices

(Figure 7). These findings suggest that the albedo visualization improved comprehensibility by helping students understand the reflective properties of surfaces.

Understanding Atmosphere: Overcoming deceptive clarity

The atmosphere plays an important role in global climate change. Students need to understand that atmosphere both acts as a shield, reflecting some energy, and as a blanket, trapping some energy in. The composition of the atmosphere determines whether the amount of energy entering the atmosphere is equal to the amount leaving. The net effect of the atmosphere is to increase the global temperature, compared with what the Earth would have without one.

In GCC1, students gave non-normative answers to the question, *If the Earth did not have an atmosphere, would the global temperature be warmer, cooler, or the same?* Analysis revealed that when students understood the atmosphere as a sort of shield, protecting the Earth from harmful rays, but not as a blanket, trapping radiation, they spent little time with the visualization, and did not change their answers from prediction to post-observation explanation. The visualization was deceptively clear for these students who assumed that the visualization confirmed their choices (Linn et al., 2010).

To overcome the deceptive clarity, we modified the prompts to encourage students to distinguish ideas about the atmosphere as a blanket and a shield. In GCC2, we found that many students improved their responses to the question, *If the Earth did not have an atmosphere, would the global temperature be warmer, cooler, or the same*, after interacting with the visualizations (correctly choosing cooler) (Figure 8). A paired-samples t-test indicated that KI scores on explanations about the atmosphere completed after interacting with a NetLogo visualization were significantly higher (M = 3.36, SD = 0.09) than predictions (M = 3.02, SD = 0.73), $t(54)$ = 2.90, p

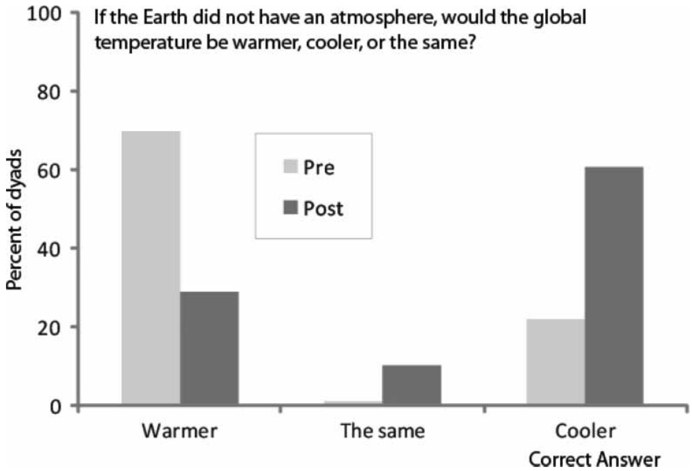


Figure 8. GCC2 responses to a predict–observe–explain sequence about the atmosphere. GCC1 responses are not pictured, but changes from pre to post were not significant

< 0.01, with a small to medium effect, $d = 0.65$. In this case, this means that after interacting with the visualization, students tended to include the idea that the atmosphere both reflects and traps energy. Focusing on distinguishing ideas by changing the prompts reduced deceptive clarity and resulted in a more coherent understanding of the role of the atmosphere.

Students' Decision-making: Structuring experimentation

In order to help students connect global climate change to personal decisions, we designed a NetLogo visualization that allowed students to test the relative impact of human activities, such as driving, eating meat, littering, and leaving the lights on when not in use. We selected activities students thought were related to global climate change (Visintainer & Svihla, 2010). We excluded decisions that were not directly feasible for middle school students, such as purchasing energy-efficient appliances and cars.

In GCC1, we included six variables (Eating meat; Littering; Driving (vs. walking) to school; Recycling paper; Recycling aluminum; Taking shorter showers). We found that students tended to change several variables at once (despite instructions requesting them to change only one at a time), consistent with findings from the earlier Global Warming unit (Varma, 2010). In GCC2, we structured inquiry by limiting the number of choices. Students could determine the relative impact of only two variables at a time. Because many students reported littering as a cause of global climate change, we contrasted littering with eating meat (For further information on impacts from meat production, see Eshel & Martin, 2006; Marlow et al., 2009.) We also contrasted driving rather than walking with leaving lights on when not in use. By structuring the experiments, we restricted the problem space and enabled students to conduct systematic investigations. We found that structuring resulted in GCC2 dyads abandoning littering in favor of eating meat as contributing greenhouse gases after interacting with the visualization (prediction $Mdn = 1$; post-observation $Mdn = 2, Z = -5.19, p < 0.001, r = 0.78$) (Table 4). Because students already believed that driving was a greater contributor of greenhouse gases compared to leaving the lights on ($Mdn = 2$ pre and post), we did not see a change from prediction to post-visualization.

In interviews ($n = 15$) and during classroom observations, students were surprised that littering did not impact global temperature. They were also surprised that eating meat did impact global temperature. Teacher comments align with these results. One-sixth grade teacher explained that she,

> really liked the global climate change unit because at the end, they're making their own suggestions as to what they think would be helpful and as to what they think they can actually do and one of the things I've noticed is they're referring back to the global climate change unit to talk about what they wanna be doing in terms of eco club and I think that is amazingly powerful.

She further explained that though the contrast between littering and eating meat was challenging, it was valuable for them to consider,

> I think the complexity of looking at the difference between littering and meat eating was really hard for them because they've been raised with 'littering as evil,' and so having them stop and actually process energy use, in terms of littering, they had a really hard time getting past the 'it's evil' mindset. And I don't disagree. I think it is evil, but in terms of energy consumption, it's fairly low, um, and, and when they were finally able to kind of get that piece, it was very helpful.

In summary, analysis of student and teacher responses to GCC1 resulted in iterative refinements to the instruction informed by the KI framework. We improved comprehensibility, added pivotal cases, and reduced deceptive clarity to help students understand the visualizations and interpret energy transformations. Findings from embedded assessments suggest that students added ideas about global climate change through visualizations of albedo and atmosphere. They applied their understanding by improving their personally relevant decisions (Table 5).

Table 4. Frequencies of sign changes of predictions to post-observation choices for decisions

	Frequencies	*n*
Driving vs. Leaving lights on	Negative differences[a]	3
	Positive differences[b]	11
	Ties[c]	30
	Total	44
Eating meat vs. Littering	Negative differences[a]	0
	Positive differences[b]	29
	Ties[c]	22
	Total	51

[a]Pre < Post

[b]Pre > Post

[c]Pre = Post

Table 5. Evidence paired with design decisions and outcomes

Improve comprehensibility of the visualizations		
Evidence	*Design change*	*Outcome*
GCC1 students provided superficial explanations ('yellow arrows turn into red dots')	Added annotated screen shots of visualizations; Match step added as check point on understanding	GCC2 students provided representational explanations ('solar radiation turns into heat energy')
Understanding energy transformation: a pivotal case		
Evidence	*Design change*	*Outcome*
Few GCC1 students explained the role of energy transformation	Added (Watch a sunray) function to visualizations and prompts to help students notice the transformations	Most GCC2 students explained the role of energy transformation
Understanding albedo: improve comprehensibility		
Evidence	*Design change*	*Outcome*
Teacher feedback prior to GCC1 indicated that albedo was challenging	Connected albedo to personal experience (ocean, farm, desert)	GCC1 students were significantly more likely to identify surfaces with high and low albedo
Understanding atmosphere: overcoming deceptive clarity		
Evidence	*Design change*	*Outcome*
GCC1 students did not describe how the atmosphere functions as a lanket and a shield	Modified prompt for atmosphere visualization: How is the atmosphere both like a shield and a blanket?	GCC2 students described how the atmosphere functions as a blanket and a shield
Students decision-making: structuring experimentation		
Evidence	*Design change*	*Outcome*
GCC1 students did not make different choices after using the visualization with six variables	Two visualizations with two variables each	GCC2 dyads were significantly more likely to correctly select eating meat as the variable contributing to greenhouse gases after interacting with the visualization

Results

To demonstrate that the refinements of GCC1 helped students gain coherent ideas about global climate change, we assess the changes in performance on the KI assessment between GCC1 and GCC2. To illustrate the impact on the understanding of energy transfer and energy transformation, we analyze MySystem diagrams and energy stories.

Knowledge Integration Assessment

Students in GCC1 and GCC2 responded to the MC and explanation parts of the KI item. For the MC part, we found no significant difference between groups at the pre-test, $F(1, 127) = 0.00$, $p > 0.05$. GCC2 students had significantly higher KI scores by the post test, $F(1, 81) = 7.94$, $p < 0.05$, with a small effect, $r = 0.30$. For the explanation component, there was no significant difference between groups at the pre-test, $F(1, 126) = 0.12$, $p > 0.05$. GCC2 students had significantly higher KI scores by the post test, $F(1, 81) = 5.30$, $p < 0.05$, with a small effect, $r = 0.24$ (Figure 9). Overall, GCC1 students moved from non-normative responses to making partial links, whereas GCC2 students additionally moved to making full and complex links, meaning that they built on relevant ideas to form scientifically normative connections by the end of the unit. This means that at the beginning of the unit, students tended to give explanations in which ozone was used as a cause, or in which temperature was ascribed to carbon dioxide as a specific property. By the end of the unit, GGC1 students tended to explain that carbon dioxide is associated with warmer temperatures. Demonstrating their understanding that the atmosphere acts like a blanket, GCC2 students tended to explain that the energy was trapped in the atmosphere by the carbon dioxide, causing temperatures to increase.

Although students made significant gains in both GCC1 and GCC2, the gains were higher and the effect sizes generally larger for GCC2. Both groups developed more coherent understanding of energy transfer. GCC2 respondents were more likely to provide explanations that involved energy transformation.

MySystem

At the pre-test, the mean KI score for energy ideas on the MySystem diagram was 2.34 (*SD* 1.25) for GCC1 and 2.70 (*SD* 1.15) for GCC2, and at the post-test, 2.53 (*SD* 1.42) for GGC1 and 3.13 (*SD* 1.60) (Figures 10 and 11). There is a significant main effect for time (pre-test to post-test) $F(3, 95) = 6.991$, $p < 0.001$, $\eta^2 = 0.18$. The effect of GCC version is not significant, $F(1, 95) = 0.482$, $p > 0.05$, $\eta^2 = 0.005$. The interaction between GCC version and time (pre-test to post-test) approaches significance, $F(2, 95) = 2.51$, $p = 0.06$, $\eta^2 = 0.07$. Overall, students

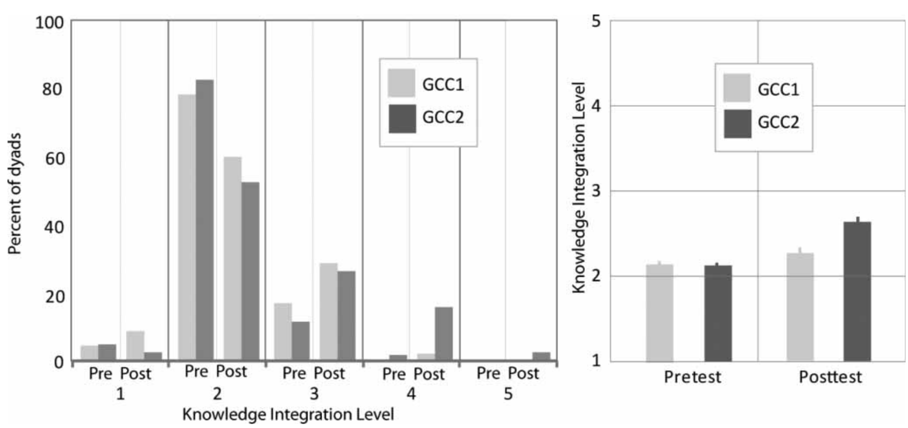


Figure 9. Percent of dyads for each knowledge integration level before and after the Global Climate Change unit and average changes for the explanation associated with the coal question

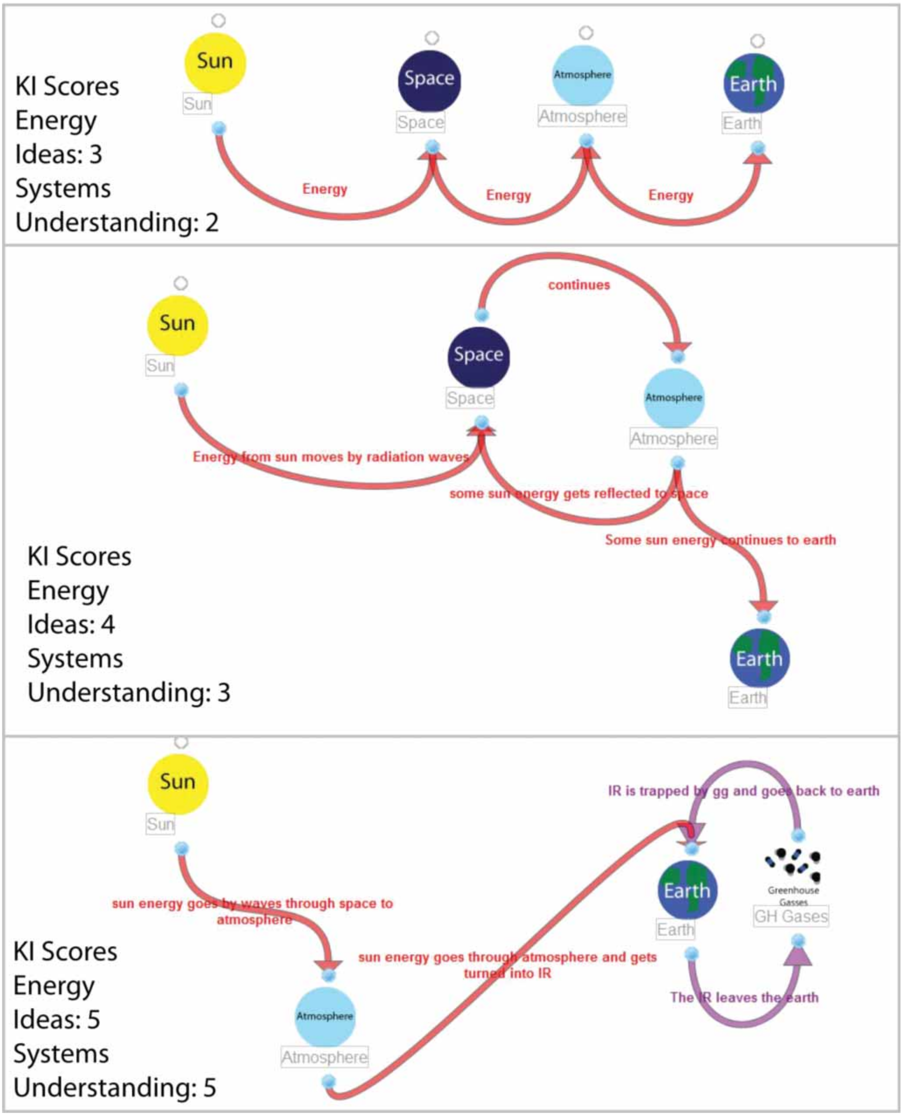


Figure 10. Samples of students' scores on MySystem diagrams

tended to provide more normative energy ideas on the post-test MySystem than on the pre-test MySystem diagram.

At the pre-test, the mean KI score for systems understanding on the MySystem diagram was 2.14 (SD 0.46) for GCC1 and 2.43 (SD 0.88) for GCC2, and at the post-test, 2.17 (SD 0.62) for GGC1 and 2.76 (SD 1.25) (Figures 10 and 11). Consistent with the findings for energy ideas, there is a significant main effect for time $F(3, 96) = 5.28$, $p < 0.01$, $\eta^2 = 0.14$, and the effect of GCC version is not significant, $F(1, 96) = 2.82$, $p > 0.05$, $\eta^2 = 0.029$. There is a significant interaction effect between version and time, $F(2, 96) = 5.72$, $p < 0.01$, $\eta^2 = 0.12$. Overall,

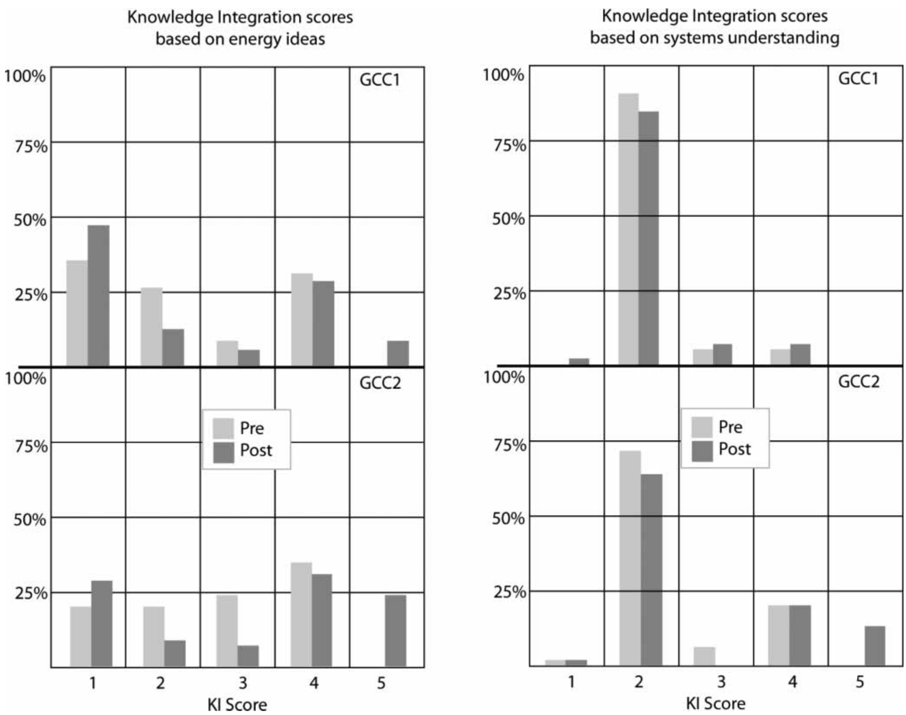


Figure 11. Knowledge integration scores related to energy ideas and systems understanding on MySystem diagrams

students displayed a more normative systems understanding on the post-test MySystem diagram. Only students who completed GCC2 represented feedback in their MySystem diagrams, consistent with the interaction effect for version.

GCC1 Energy Stories

GCC1 students' energy stories were significantly more coherent at the end of the unit ($M = 3.65$, $SD = 0.84$) than at the beginning ($M = 3.19$, $SD = 0.82$), $t(47) = 2.86$, $p < 0.01$, with a medium effect size, $d = 0.55$ (Figure 12). Overall, students moved from making partial links to making full links, meaning that they built on relevant ideas to form scientifically normative connections by the end of the unit. At the beginning of the unit, students tended to give vague explanations about energy coming from the Sun and reaching the Earth. By the end of the unit, students tended to include a normative explanation about how the energy was transferred, but they rarely explained how energy was transformed (Table 6).

GCC2 Energy Stories

GCC2 students' energy stories were significantly more coherent at the end of the unit ($M = 4.35$, $SD = 0.84$) than at the beginning ($M = 3.12$, $SD = 0.98$), $t(47) = 7.43$,

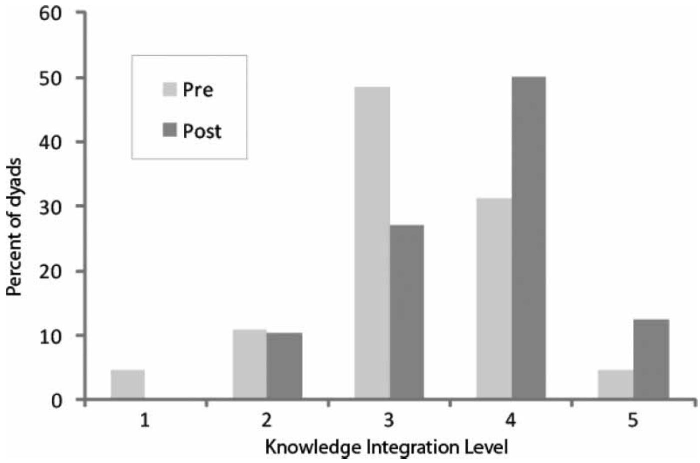


Figure 12. Percent of dyads for each knowledge integration level on energy stories completed before and after GCC1

$p < 0.001$, with a large effect size, $d = 1.35$ (Figure 13). Overall, students moved from making partial and full links to making full and complex links, meaning that they built on relevant ideas to form scientifically normative, and elaborated connections by the end of the unit. At the beginning of the unit, students tended to give vague explanations about energy coming from the Sun and reaching the Earth. By the end of the unit, students tended to include a normative explanation about how energy was transferred. Many students also explained how energy was transformed (Table 6). Because we refined the energy story prompt for GCC2, we cannot attribute the greater gains to the design changes.

Discussion

Students studying both versions of GCC gained coherent ideas about energy. GCC2 students gained more integrated understanding than GCC1 students as shown on KI assessments. Specific responses to energy stories and MySystem clarify that students were able to integrate ideas about energy transformation as a result of improvements to GCC1.

GCC1 students gained understanding of the role of energy transfer in global climate change, but they did not integrate ideas related to energy transformation, a critical piece for understanding mechanisms for global climate change. Rather than explaining how energy itself might change from one type to another type (e.g., from solar radiation to thermal energy), students tended to either omit the mention of transformation entirely or to use it to describe changes in location or non-normative changes (e.g., energy changing into matter). They also did not change their ideas about which activities contribute greenhouse gases to the atmosphere.

Based on evidence from GCC1, we improved comprehensibility of the visualizations, added a pivotal case to distinguish reflection and transformation, added

Table 6. Sample post-project energy stories from GCC1, highlighting the evidence of energy transfer, but not transformation, and from GCC2, highlighting the evidence of both energy transfer and transformation

KI score	GCC1	KI score	GCC2
4	Well, energy comes from the Sun which transfers to the Earth by radiation. Energy moves by radiation. Energy moves from the Sun and transfers to the Earth. Energy changes when global climate changes or it changes by the pattern of air in the sky when transfering	5	The sun sends solar radiation to the Earth. Some of the solar radiation is absorbed and some makes it to Earth. Some of the radiation gets reflected and some gets absorbed and changes into heat energy. When the absorbed radiation escapes from the Earth it can change into infrared radiation. Some of the infrared radiation gets reflected by the clouds and greenhouse gases and bounces back instead of escaping to space.
4	Energy and radiation come from the sun. When energy moves, it transfers from the Sun to the Earth by radiation. If clouds are in the way, the Sun's radiation gets blocked, but some still passes through. Energy goes to the Earth and energy changes in different ways that it is used. Some energy is used as electricity. Some is used for gas or for cars. Also, some is just used for batteries. Energy can be supported in many different ways. But some energy goes to greenhouse gases. The only problem is energy pollutes our atmosphere with so called global warming and we need to use energy more efficiently to save our atmosphere	5	The energy initially comes from the Sun. It emits solar radiation, which travels through space and hits the atmosphere. There, it is either reflected by the clouds or travels all the way to the surface. Once at the surface, some of it bounces off and stays as solar radiation as it goes back into the space. The rest of the solar radiation is absorbed into the crust and becomes thermal energy. This heats up the surface. This thermal energy is eventually released as infrared radiation, which goes into the atmosphere. This heats up the atmosphere. The infrared radiation bounces around in the atmosphere, reflecting off things such as pollutants, water molecules, and greenhouse gases

activities to reduce deceptive clarity, and structured experimentation, following the KI framework. Evidence from GCC2-embedded assessments suggests that these changes were successful. Students had good understanding of the visualizations. They gained insight into climate change variables such as the atmosphere and albedo by interacting with visualizations. They could make evidence-based decisions about everyday activities related to energy use and carbon production as a result of interactions with the visualizations. These changes improved overall KI as well as specific understanding of energy transformation (Table 6).

In summary, GCC2 students made larger pre-test–post-test gains in understanding the role of energy transfer and transformation than did GCC1 students on KI items and MySystem responses. In GCC2, students were likelier to include energy

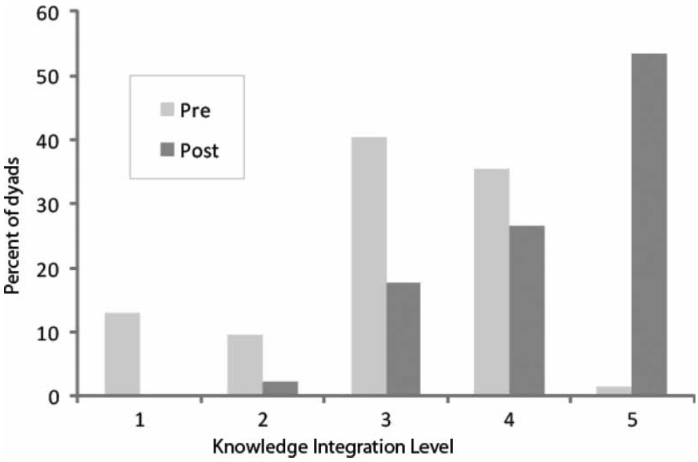


Figure 13. Percent of dyads for each knowledge integration level on energy stories completed before and after the second iteration of the Global Climate Change unit

transformations in their explanations, and feedback loops in their MySystem diagrams. Of course, other factors beyond the design changes may also have contributed to the differing learning gains across the two iterations.

In conclusion, by improving comprehensibility, adding pivotal cases, structuring experimentation to distinguish ideas, and reducing deceptive clarity, we strengthened the impact of the visualizations in GCC1. Detailed coding of the ideas and connections students formed in GCC1 allowed us to use the KI framework to guide strategic changes to the curriculum. As a result, students in GCC2 had more integrated understanding of energy transfer and gained insight into energy transformation compared with students in GCC1.

These findings show that middle school students can learn about complex systems when the curriculum is carefully designed. They underscore the importance of using evidence from student work to guide iterative refinement of instruction. They offer guidance for designers of science instruction, suggesting the value of the KI pattern and specifically the importance of structuring investigations to focus on distinguishing ideas.

Acknowledgements

NSF funding under grant 0822388 is gratefully acknowledged. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy.* New York: Oxford University Press.

Andersson, B., & Wallin, A. (2000). Students' understanding of the greenhouse effect, the societal consequences of reducing CO_2 emissions and the problem of ozone layer depletion. *Journal of Research in Science Teaching*, *37*(10), 1096–1111.

Bell, P. (2000). Scientific arguments as learning artifacts: Designing for learning from the web with KIE. *International Journal of Science Education*, *22*(8), 797–817.

Blumenfeld, P.C., Soloway, E., Marx, R.W., Krajcik, J.S., Guzdial, M., & Palincsar, A.S. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. *Educational Psychologist*, *26*(3), 369–398.

Chiu, J.L., & Linn, M.C. (in press). The role of self-monitoring in learning chemistry with dynamic visualization. In A. Zohar & Y.J. Dori (Eds.), *Metacognition and science education: Trends in current research* (Vol. 40, p. 306). London: Springer-Verlag.

Collins, A., & Brown, J. (1988). The computer as a tool for learning through reflection. In H. Mandl & A. Lesgold (Eds.), *Learning issues for intelligent tutoring systems* (pp. 1–18). New York: Springer-Verlag.

Corbin, J.M., & Strauss, A. (1990). Grounded theory research: Procedures, canons, and evaluative criteria. *Qualitative Sociology*, *13*(1), 3–21.

Cordero, E., Marie Todd, A., & Abellera, D. (2008). Climate change education and the ecological footprint. *Bulletin of the American Meteorological Society*, *89*(6), 865–872.

Curriculum Development and Supplemental Materials Commission. (2003). *Science Framework for California Public Schools Kindergarten Through Grade Twelve*. Sacramento, CA: California Department of Education.

Davis, E. (2004). Creating critique projects. In M.C. Linn, E. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 89–114). Mahwah, NJ: Lawrence Erlbaum Associates.

Edelson, D. (2002). Design Research: What We Learn When We Engage in Design. *Journal of the Learning Sciences*, *11*(1), 105–121.

Edelson, D., Gordin, D., & Pea, R. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences*, *8*(3), 391–450.

Eshel, G., & Martin, P. (2006). Diet, energy, and global warming. *Earth Interactions*, *10,* 1–17.

Gunstone, R.F., & Champagne, A.B. (1990). Promoting conceptual change in the laboratory. In E. Hegarty-Hazel (Ed.), *The student laboratory and the science curriculum* (pp. 159–182). New York: Routledge.

Joachimski, M., Breisig, S., Buggisch, W., Talent, J., Mawson, R., Gereke, M., … Weddige, K. (2009). Devonian climate and reef evolution: Insights from oxygen isotopes in apatite. *Earth and Planetary Science Letters*, *284*(3–4), 599–609.

Krajcik, J., Blumenfeld, P., Marx, R., Bass, K., Fredricks, J., & Soloway, E. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. *Journal of the Learning Sciences*, *7*(3), 313–350.

Krajcik, J., Slotta, J.D., McNeill, K.L., & Reiser, B. (2008). Designing learning environments to support students' integrated understanding. In Y. Kali, M.C. Linn, & J. Roseman (Eds.), *Designing coherent science education* (pp. 39–64). New York: Teachers College Press.

Lee, H.-S., & Liu, O.L. (2010). Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective. *Science Education*, *94*(4), 665–688.

Le Quéré, C., Raupach, M.R., Canadell, J.G., & Marland, G. (2009). Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, *2*(12), 831–836.

Linn, M.C. (2006). The knowledge integration perspective on learning and instruction. In K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 243–264). New York: Cambridge University Press.

Linn, M.C., Bell, P., & Davis, E. (2004). Specific design principles: Elaborating the scaffolded knowledge integration framework. In M.C. Linn, E. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 315–339). Mahwah, NJ: Lawrence Erlbaum Associates Publishers.

Linn, M.C., Chang, H.-Y., Chiu, J., Zhang, H., & McElhaney, K.W. (2010). Can desirable difficulties overcome deceptive clarity in scientific visualizations? In A. Benjamin (Ed.), *Successful remembering and successful forgetting: a Festschrift in honor of Robert A. Bjork* (pp. 239–262). New York: Routledge.

Linn, M.C., & Clancy, M. (1992). The case for case studies of programming problems. *Communications of the ACM*, *35*(3), 121–132.

Linn, M.C., & Eylon, B.-S. (2011). *Science learning and instruction: Taking advantage of technology to promote knowledge integration*. New York: Routledge.

Linn, M.C., & Hsi, S. (2000). *Computers, teachers, peers: Science learning partners*. Mahwah, NJ: Lawrence Erlbaum.

Linn, M.C., Lee, H., Tinker, R., Husic, F., & Chiu, J. (2006). Teaching and assessing knowledge integration in science. *Science*, *313*(5790), 1049–1050.

Liu, L., & Hmelo-Silver, C. (2009). Promoting complex systems learning through the use of conceptual representations in hypermedia. *Journal of Research in Science Teaching*, *46*(9), 1023–1040.

Marlow, H., Hayes, W., Soret, S., Carter, R., Schwab, E., & Sabate, J. (2009). Diet and the environment: does what you eat matter? *American Journal of Clinical Nutrition*, *89*(Supplement), 1S–5S.

Mohan, L., Chen, J., & Anderson, C. (2009). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *Journal of Research in Science Teaching*, *46*(6), 675–698.

Quintana, C., Reiser, B.J., Davis, E.A., Krajcik, J., Fretz, E., Duncan, R.G., … Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences*, *13*, 337–386.

Reiser, B.J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. *Journal of the Learning Sciences*, *13*(3), 273–304.

Reiser, B.J., Tabak, I., Sandoval, W.A., Smith, B.K., Steinmuller, F., & Leone, A.J. (2001). BGuILE: Strategic and conceptual scaffolds for scientific inquiry in biology classrooms. In S.M. Carver & D. Klahr (Eds.), *Cognition and instruction: Twenty-five years of progress* (pp. 263–305). Mahwah, NJ: Lawrence Erlbaum.

Roediger, H., & Karpicke, J. (2006). Test-enhanced learning. *Psychological Science*, *17*(3), 249.

Sandoval, W. (2003). Students' understanding of causal explanation and natural selection in a technology-supported inquiry curriculum. *The Journal of the Learning Sciences*, *12*, 5–51.

Sandoval, W., & Reiser, B. (2004). Explanation-driven inquiry: Integrating conceptual and epistemic scaffolds for scientific inquiry. *Science Education*, *88*(3), 345–372.

Scardamalia, M., & Bereiter, C. (1991). Higher levels of agency for children in knowledge building: A challenge for the design of new knowledge media. *The Journal of the Learning Sciences*, *1*(1), 37–68.

Simon, L., & Goddéris, Y. (2007). Modeling the carbon and sulfur isotope compositions of marine sediments: Climate evolution during the Devonian. *Chemical Geology*, *246*(1–2), 19–38.

Slotta, J., & Linn, M.C. (2009). *WISE science: Web-based inquiry in the classroom*. New York: Teachers College Press.

Varma, K. (2008). Supporting students' experimentation strategies with dynamic visualizations. In P.A. Kirschner, F.J. Prins, V. Jonker, & G. Kanselaar (Eds.), *Proceedings of the 8th International Conference of the Learning Sciences, international perspectives in the learning sciences: Cre8ting a learning world* (Vol. 3, pp. 221–228). Utrecht, The Netherlands: International Society of the Learning Sciences.

Varma, K. (2010). Using interactive models to support content learning through scientific reasoning. In K. Gomez, A. Lyons, & J. Radinsky (Eds.), *Learning in the disciplines: Proceedings of the 9th International Conference of the Learning Sciences (ICLS)*. Chicago, IL, USA: International Society of the Learning Sciences, 2, 232–233.

Visintainer, T., & Svihla, V. (2010). Redesigning global climate change for cumulative learning. In K. Gomez, L. Lyons, & J. Radinsky (Eds.), *Learning in the disciplines: Proceedings of the 9th International Conference of the Learning Sciences (ICLS)* (Vol. 2, pp. 255–256). Chicago, IL: International Society of the Learning Sciences.
Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep, or a firefly: Learning biology through constructing and testing computational theories—an embodied modeling approach. *Cognition and Instruction*, *24*(2), 171–209.