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Sixth-Grade Students' Progress in Understanding the Mechanisms of Global Climate Change

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Abstract Developing solutions for complex issues such as global climate change requires an understanding of the mechanisms involved. This study reports on the impact of a technology-enhanced unit designed to improve understanding of global climate change, its mechanisms, and their relationship to everyday energy use. Global Climate Change, implemented in the Web-based Inquiry Science Environment (WISE), engages sixth-grade students in conducting virtual investigations using NetLogo models to foster an understanding of core mechanisms including the greenhouse effect. Students then test how the greenhouse effect is enhanced by everyday energy use. This study draws on three data sources: (1) pre- and post-unit interviews, (2) analysis of embedded assessments following virtual investigations, and (3) contrasting cases of two students (normative vs. non-normative understanding of the greenhouse effect). Results show the value of using virtual investigations for teaching the mechanisms associated with global climate change. Interviews document that students hold a wide range of ideas about the mechanisms driving global climate change. Investigations with models help students use evidence-based reasoning to distinguish their ideas. Results show that understanding the greenhouse effect offers a foundation for building connections between everyday energy use and increases in global temperature. An impediment to establishing coherent understanding was the persistence of an alternative conception about ozone as an explanation for climate change. These findings illustrate the need for regular revision of curriculum based on classroom trials. We discuss key design features of models and instructional revisions that can transform the teaching and learning of global climate change.

Keywords Global climate change · Mechanisms · Virtual investigations · Models · Everyday energy use

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Introduction

Global climate change is a complex environmental issue with significant socio-ecological implications. Innovative problem-solving and decision-making skills are needed at a range of levels from the professional scientific community to the individual citizen to address the problem. To make informed decisions about the climate, citizens need to understand the mechanisms that drive global climate change and the contribution of everyday actions to these mechanisms. Appreciating the cumulative effect of anthropogenic factors on the climate requires innovative approaches to instruction, especially given the many conflicting messages students are likely to encounter in the media and other outlets. To contribute to this goal, we investigated students' ideas before, during, and after studying a unit on global climate change to characterize the impact of instruction and to identify ways to strengthen the unit.

Promoting Mechanistic Reasoning

We explore how students explain global climate change as a result of instruction. We look for increases in their understanding and use of scientific mechanisms for explaining global climate change. For example, students could gain understanding of how natural warming mechanisms are enhanced by anthropogenic processes (e.g. everyday energy use). Russ et al. (2008) argue for a focus on mechanistic reasoning as an important part of scientific inquiry. This is consistent with the National Research Council's (2000) call for reform of science curricula that allows students to gain deep understanding of fundamental concepts, make connections to the real world through inquiry, and use scientific reasoning to make societal and personal decisions. Developing this ability will allow students to critique scientific work, analyze information, and gain an understanding of how to apply science knowledge and skills to real world problems in the future. Understanding the depth and structure of students' domain knowledge can help designers improve instruction (Lehrer et al. 2008). A better understanding of students' sense making about the mechanisms that underlie natural and anthropogenic global climate change-related processes can help designers create instruction that improves student reasoning.

Learning from Virtual Investigations with Models

We study how students progress in explaining global climate change as a result of studying the Web-based Inquiry Science Environment (WISE) Global Climate Change (GCC) unit. The unit uses NetLogo models (Wilensky and Reisman 2006) created by the Concord Consortium (Pallant et al. 2012) to promote mechanistic reasoning through virtual investigations and the knowledge integration framework to promote coherent understanding.

The models support student investigations that explore the core mechanisms driving global climate change and anthropogenic contributions to increases in global temperature. It resonates with the Next Generation Science Standard's emphasis on promoting "practices," including developing and using models, by using scientific inquiry to illustrate that scientific literacy requires the coordination of both knowledge and skills (NGSS 2013). Specifically, in GCC, visualizations allow students to investigate complex phenomena that they cannot directly observe. Virtual investigations allow students to make predictions, test hypotheses, and observe outcomes. Students reason about topics such as greenhouse gas production and develop explanations for complex natural and human-induced changes in global temperature, consistent with the NGSS standards. They conduct virtual investigations through options to add/remove variables (e.g. greenhouse gases), observe changes in global temperature, and record data in the form of variables changed and impacts on global temperature.

The unit is designed using the knowledge integration framework. The framework emphasizes guiding learners to make predictions based on their own ideas, to add new ideas from curriculum activities, to distinguish their predictions from their findings from virtual investigations, and to reflect on their progress. Students are supported to make predictions, conduct virtual investigations, distinguish among their ideas using evidence from investigations, and to generate coherent explanations for everyday decision making involving energy use such as choosing to walk rather than drive a car (Linn 2006). Key to this process is to help students distinguish between their initial ideas and the scientifically sophisticated ideas introduced in the unit. Essentially, the unit helps students develop more scientifically mechanistic ideas.

Activities that utilize NetLogo models within the knowledge integration framework provide activities to help students distinguish among ideas and develop a coherent account of scientific phenomena. Previous research shows that WISE units with NetLogo models can support students as they add and sort out ideas in their repertoires to explain the greenhouse effect (Varma and Linn 2012). Prior research has led to refinements to GCC including scaffolding investigations, increasing comprehension of the NetLogo models, and clarifying decisions about everyday activities related to energy use and greenhouse gas production (Svihla 2012). In this study, we examine the depth of the ideas, resources, and experiences that students bring to science class (Reeve and Bell 2009) regarding global climate change and everyday energy use and changes in students' ideas as a result of instruction.

Students' Ideas About Global Climate Change: Previous Research

Prior research illustrates the productive ideas middle school students hold and the challenges they experience in understanding the mechanisms of global climate change. This provides designers with opportunities to help students distinguish their ideas and develop a more complex understanding of the scientific mechanisms associated with global climate change through instruction. Students have difficulty understanding the mechanisms associated with global climate change including the greenhouse effect, the role of carbon dioxide (CO_2) and other greenhouse gases, and the ways that human actions contribute to the problem. Students think of greenhouse gases as existing as a layer in the atmosphere (Andersson and Wallin 2000; Shepardson et al. 2009), do not distinguish different types of greenhouse gases (Boyes and Stanisstreet 1997a), and often do not consider CO_2 a type of greenhouse gas. This means that they miss connections between CO_2 and global climate change (Mohan et al. 2009; Shepardson et al. 2009). Additionally, studies show that students do not distinguish different types of radiation involved with the greenhouse effect (Osterlind 2005; Shepardson et al. 2009).

Students across middle and high school grades connect some anthropogenic factors to global climate change but not others. Students report that human actions cause air pollution and increases in greenhouse gases (Boyes and Stanisstreet 1997a; Andersson and Wallin 2000; Shepardson et al. 2009) and view factories and vehicles as sources of air pollution (Shepardson et al. 2009). However, students often aggregate pollutants and reason that pollutants in general give rise to all environmental problems (Boyes and Stanisstreet 1997b). One study reported that students equated littering with other forms of pollution rather than recognizing that certain types of pollution (e.g. burning fuels) contribute to greenhouse gas accumulation but littering does not (Svihla 2012). Students also hold alternative conceptions about human contributions to global climate change. Some primary and secondary students report that car emissions contribute to ozone layer depletion, while others are challenged by issues of scale arguing that heat from car exhaust heats the environment at global levels (Boyes and Stanisstreet 1997b).

Finally, students have fruitful ideas about resolving issues associated with global climate change but have difficulty understanding the connection between different components of ecological systems, and predicting the impact of global climate change on their lives. They suggest planting trees, reducing CO_2 emissions, driving less, recycling, and polluting less (Kilinc et al. 2008; Shepardson et al. 2009). However, students often see these ideas as generally valuable for saving energy or improving the environment rather than specifically relevant to global warming (Boyes and Stanisstreet 1997b). In addition, students rarely connect the effects of global climate change to the complex interdependence of plants and animals and may not believe that climate change will have an impact on themselves or society in their lifetimes (Shepardson et al. 2009). These studies illustrate the value of using the knowledge integration framework to design instruction by documenting the complex, varied, and contradictory repertoires of ideas students hold about global climate change.

This work furthers our understanding of how students conceptualize the mechanisms associated with global climate change and how conducting virtual investigations shapes students' reasoning and the connections they make between human activities and increases in global temperature. This study addresses the following research questions:

- How do students conceptualize the scientific mechanisms associated with global climate change before and after interaction with the unit? What evidence sources do students draw from to support their initial ideas? How do students negotiate their everyday and instructed ideas as they study GCC?
- How do virtual investigations using models affect students' understanding of the scientific mechanisms associated with global climate change and the connections made between scientific mechanisms and everyday energy use?

This research clarifies how students use virtual investigations to understand global climate change. It informs the design of instruction that supports understanding of the connections between everyday actions and the scientific mechanisms that drive global climate change.

Overview of Methods

Research Design

To address our research questions, we use three data sources: (1) pre- and post-unit semi-structured student interviews, (2) analysis of embedded assessments following virtual investigations, and (3) contrasting cases of one student with complete, scientifically acceptable (i.e. normative) and one student with non-normative understanding of the greenhouse effect.

We use quantitative and qualitative methods including interviews and embedded assessments to explore how different evidence sources influence students' ways of thinking about global climate change (Reeve and Bell 2009; Shepardson et al. 2009) and how virtual investigations with models help students critique scientific work, analyze information, and apply science knowledge and skills to real world problems. This study extends previous approaches to understanding middle school students' conceptions of global climate change that include written task assessments (Andersson and Wallin 2000) and questionnaires (Boyes et al. 1993). The goal of this approach is to track the repertoire of ideas students hold as they study GCC and to capture the processes associated with changes (Cole and Scribner 1974) by making links between the instruction and students' ideas.

Participants

186 sixth-grade students completed the GCC unit at three different racially/ethnically and socioeconomically diverse public middle schools (grades 6–8) in a Northern California metropolitan area. Pre- and post-unit interviews were conducted with 15 sixth-grade students, five students each from three different sixth-grade classrooms at two different schools. Schools were selected because they were running GCC in their classrooms when this research was conducted. Interviewees were selected to capture a diverse range of students with varying backgrounds and

experiences. Eight girls and seven boys were interviewed from a variety of races/ethnicities and socioeconomic backgrounds. From the pool of 15 student interviewees, we selected two case study students (Justin and Carson) in order to obtain a more in-depth understanding of how students' thinking and reasoning changed and aligned with specific aspects of the instructional intervention. The two case study students were both boys from the same sixth-grade science class/school and should have experienced the curriculum in similar ways. The names of all students, including Justin and Carson, have been changed and replaced with pseudonyms. Students completed all work related to the GCC unit in dyads over the course of the 7 days of instruction.

Instructional Overview

We designed GCC, a 7-day unit, as part of a larger design-based research collaborative featuring energy-related WISE units. We made revisions to an earlier version of GCC based on findings from a pilot study with four classes of sixth-grade students. We found that students commonly cited littering as a cause for global climate change and tended to group all types of environmental issues together. The revised GCC unit contains eight main activities and utilizes virtual investigations with five NetLogo models. The version of GCC used in this study is the same version referred to as GCC2 in previous studies (Svihla 2012). The goal of GCC is to facilitate understanding of core mechanisms associated with global climate change and to help students make connections between their own experiences with energy consumption and the mechanisms of global climate change. The intervention is designed to address these cognitive objectives in the following ways:

1. *Knowledge construction based on everyday experiences*. At the beginning of the unit, students make predications about everyday energy consumption and the impact these actions might have on global temperature. At the end of the unit, students compare the effect of different everyday actions on global temperature in order to gather evidence, build on, and distinguish their initial ideas. The instructional goal is for students to build understanding of why global temperature increases and how anthropogenic factors contribute to these temperature increases.
2. *Understanding of domain-specific mechanisms and processes*. Students conduct virtual investigations with NetLogo models by testing different variables associated with global climate change and making observations about impacts on global temperature that is graphed in real time adjacent to the model (see Fig. 1). Investigations with NetLogo models facilitate learning of the following core mechanisms associated with global climate change: (1) transformation of solar radiation to heat and infrared radiation (IR), (2) the effect of albedo (% reflected light) on global temperature, (3) the role of the atmosphere and greenhouse gases in sustaining global temperature, (4) the greenhouse effect, (5) natural and anthropogenic sources of greenhouse gas production, focusing on accumulation of carbon dioxide over time, and (6) the impact of energy consumption (e.g. cars, electricity) and different everyday actions on global temperature.
3. *Scientific reasoning*. Students experiment with NetLogo models to investigate the principle sources of evidence for human contributions to global climate change involving energy consumption. Reflective prompts following virtual investigations require students to reason about how human actions at all levels (e.g. home vs. commercial factory) affect greenhouse gas production and global temperature. The reflective prompts are scaffolded in a way that requires students to reason about new evidence gathered during virtual investigations and to build on understanding constructed in previous steps.

Data Sources and Analysis

Student interviews were conducted to elicit students' ideas about global climate change-related mechanisms before and after completion of the unit. Pre-unit interviews established a baseline for students' ideas and understanding of the mechanisms associated with global climate change. Post-unit interviews determined changes in students' understanding and mechanistic reasoning following completion of the unit. Embedded assessments provided an analysis of student reasoning during the unit and allowed for examination of how students utilized NetLogo models to gather evidence, develop understanding of mechanisms, and apply their ideas to real world scenarios. Detailed analysis of interview responses and embedded assessments for two students selected from the pool of interviewees provides an in-depth analysis of trajectories of the development, refinement, and expansion of students' repertoires of ideas throughout the unit.

Student Interviews

Pre-unit interviews were conducted with 15 students prior to starting the GCC unit. Post-unit interviews were conducted the day following completion of the unit. Interviews were conducted one-on-one with the lead author at the students' school sites. All interviews were audio recorded and transcribed.

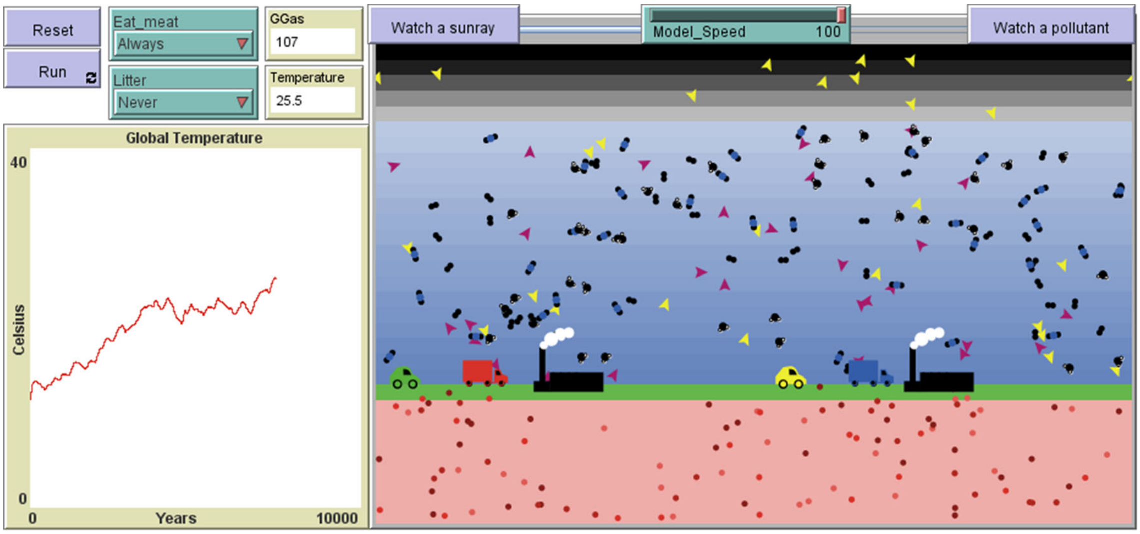

Fig. 1 GCC NetLogo simulation of the enhanced greenhouse effect illustrating anthropogenic contributions to greenhouse gas production and interaction of greenhouse gases with infrared radiation. Students conduct virtual investigations by changing variables on the *top* of the model and observing changes in global temperature graphed in real time on *left*. Model features are as follows: *yellow arrows* = sun rays, *black circles* = greenhouse gases, *red circles* = transformation of sunrays to heat energy, and *purple arrows* = infrared radiation (Color figure online)

We used descriptive and structural questions (Spradley 1979) in order to capture a holistic picture of students' conceptions of the mechanisms associated with global climate change and the evidence students use to support their ideas. Structured prompts were used when needed to gain greater insight into students' reasoning about the mechanisms involved with global climate change (see Appendix 1: Pre-unit interview protocol, see Appendix 2: Post-unit interview protocol). To determine the sources of evidence that students draw from to support their ideas, following each structured prompt and/or scenario, students were asked where they got their ideas during pre-unit interviews (see Appendices 1, 2).

Interview Analysis

Interviews were coded for students' ideas and reasoning about why global temperature might increase (i.e. warming mechanisms). Coding was done inductively, and categories for the emergent ways students described the mechanisms associated with global climate change were constructed through an iterative process (Miles and Huberman 1994). Coding categories emerged from the data and were not predetermined. First, transcripts were read through in their entirety, and statements involving warming mechanisms were noted. Second, phrases involving warming mechanisms were coded as ideas. Students' sense making and the meaning they associated with these ideas were inferred through analysis of their statements before and after the phrase to provide sufficient context. Third, codes were developed and refined in collaboration with colleagues. The lead author presented an initial coding scheme and definitions of coding categories to a research group consisting of faculty, postdoctoral scholars, discipline experts, and graduate students. The number of coders involved in the process ranged from two to five coders throughout the process. Categories were refined through the process of collaboration with the researchers interpreting and applying the codes to sections of interview transcripts (Hammer and Berland 2014). Disagreements arose about the types of mechanisms that the codes represented—such as "warming" and "energy-related" mechanisms. Multiple coders had difficulty differentiating between several codes within this original coding scheme. In addition, since students hold multiple ideas about global climate change that often fall into more than one category, this added to the complexity of the coding task. Disagreements regarding application of the codes led to further discussion of the coding categories, re-analysis of the data, and refinement of the coding scheme (Hammer and Berland 2014) (see Table 1 for final coding scheme). A similar process was used to determine categories for the sources of evidence students draw from to support their ideas.

It should be noted that because coding categories emerged from students' ideas during interviews, the definitions of codes reflect how students described their ideas about warming mechanisms, rather than scientifically acceptable definitions for particular warming mechanisms. For example, students who cited "the sun" described sun light as getting warmer leading to an increase in temperature. Therefore, "sun light is getting warmer" is the definition for the coding category "sun" presented in the coding scheme (see Table 1). In addition, the intention of the warming mechanisms coding scheme (see Table 1) was

Table 1 Pre- and post-unit global climate change mechanism categories, subcategories, and number of students citing category

Warming Mechanism	No. of Students ($n = 15$) Pre	Post	Description	Example: Student Quote
Anthropogenic Mechanisms				
Ozone				
Holes (in general)	4	3	Holes in ozone let sunlight in	The ozone layer is opening, and it's letting in ultraviolet radiation and it's getting hotter.
Energy-use-related products: destroy ozone/get trapped	5	4	Related specifically to energy use: products from energy use (e.g. cars, electricity) destroy ozone layer; ozone traps energy-use-related products (e.g. CO_2) inside of it	We are producing a lot of CO_2 and CO_2 gets trapped in the atmosphere by the ozone layer, and then it gets reflected…back into the earth…so the heat is making everything hotter.
Pollution				
General	5	1	Pollution in general increases temperature (no specific mechanism).	Pollution may be making it warmer.
Effects clouds/atmosphere	5	0	Clouds/atmosphere: pollution effects/makes more clouds, etc.	It (pollution) is going up into the atmosphere and it's making more clouds which hold heat inside.
Is warm (energy-related)	7	5	Pollution (gas/exhaust/smog/smoke) literally is warm	My dad got a car, I saw…there was kind of smoke coming out of the car and it was really hot. Every car that I see pass by I see that coming out.
Created by energy process	8	10	Pollution/CO_2 is produced by power plants, factories, and byproduct from burning coal/fuel	I think we get most of our electricity by burning coal…like the burning of coal would emit a lot of a lot of pollution into the air.
[Destroys ozone (*counted in Ozone*)]				
Landfills	1	0	Decomposing garbage produces heat; there are many big landfills so this warms the planet	The garbage it…starts to decompose…it puts off a lot of heat and that can make the planet warmer.
Chemicals/oil	4	0	Oil, trash, sewage, etc. in the water melts ice	Well animals die from the oil in the water…it could be separating the ice.
Energy-related: object produces heat	3	1	Object that uses energy literally produce heat that contributes to increases in global temperature	When you use a light bulb and you turn it on…take it out you have to use a glove cause its really hot. Maybe when you open the door the hot air gets out and cold air gets in and it goes on and on.
Energy related: enhanced Greenhouse effect (*post only*)	0	5	Human actions involving energy use increase the production of greenhouse gases (e.g. through burning fossil fuels). This enhances the natural greenhouse effect (i.e. #3) by reflecting more infrared radiation and accelerating warming	Burning fossil fuels emits CO_2 and when rays come down and are turned into infrared rays they bounce back from the greenhouse gases and stay.
Natural Mechanisms				
Sun	2	1	Sun light is getting warmer; spreading around more	Well, the sun is maybe getting hotter and its melting Antarctica.
Greenhouse gases/carbon dioxide (CO_2)	2	14	Greenhouse gases reflect heat/infrared radiation back to earth; greenhouse gases build up in the atmosphere	In the project it showed a timeline of gases released by different stuff, it builds up in our atmosphere.
Albedo (*post only*)	0	3	Sunlight is absorbed by/reflected off the ground at different rates depending on the type of landscape	Solar radiation might get reflected by the ground depending on the kind of albedo, that the ground has or surface.
Green house effect (*post only*)	0	14	Solar radiation (sunlight) transforms into infrared radiation, bounces/reflects off of greenhouse gases back to earth and stays making the earth warmer	Because it's (solar radiation) not in the form of sunlight anymore, it's in the form of infrared radiation… the heat is turning into IR, it's bouncing off the greenhouse gases back to earth, so it just gets warmer and warmer.
Radiation transformation (*post only*)	0	6	Sunlight comes to earth in the form of solar radiation and transforms into infrared radiation; sunlight reaches earth, transforms into heat, and then leaves as infrared radiation	The sunlight goes into the ocean, turns into heat energy, and some of it goes out as infrared radiation.

The majority of students cited multiple categories of ideas; therefore, the number of ideas in the table is greater than the total number of students interviewed. However, students' ideas in a single category were counted only once (even if they cited the idea multiple times) to represent the range of students' ideas regarding increases in global temperature rather than to score ideas for scientific accuracy. Therefore, discussions of students' ideas refer only generally to ideas as complete (i.e. scientifically acceptable), partial (i.e. a combination of scientifically acceptable and incomplete or alternative ideas), or alternative (i.e. scientifically inaccurate) to give a general sense of where ideas fall on a continuum and to show the range of understandings that exist.

Assessment of Students' Ideas

Through analysis of the interview data, several ideas about core warming mechanisms emerged: radiation transformation, interaction of greenhouse gases and infrared radiation, the greenhouse effect, and the enhanced greenhouse effect. These core ideas were scored as normative or non-normative to determine how differences in scientific accuracy of understanding impacted students' reasoning about everyday actions involving energy use and increases in global temperature. As with the coding scheme above, definitions for normative versus non-normative responses were discussed with the research group. The following definitions for *normative* accounts of core mechanisms were agreed upon after multiple rounds of refinement: (1) radiation transformation: sunlight comes to earth in the form of solar radiation and transforms into infrared radiation; or sunlight reaches earth, transforms into heat, and then leaves as infrared radiation, (2) interaction of greenhouse gases (CO_2) and infrared radiation: greenhouse gases build up in the atmosphere and reflect infrared radiation, (3) greenhouse effect: solar radiation (sunlight) transforms into infrared radiation, bounces/reflects off of greenhouse gases back to earth, and stays making the earth warmer, (4) enhanced greenhouse effect: human actions involving energy use increase the production of greenhouse gases (e.g. through burning fossil fuels). This enhances the natural greenhouse effect (i.e. #3) by reflecting more infrared radiation and accelerates warming.

The goal of instruction was to allow students to build on complete or partial understandings and to challenge alternative conceptions. The quality and sophistication of student reasoning was analyzed by examining shifts in students' repertories of ideas and assessing whether students were able to make use of the tools provided throughout the unit in order to reason about and make connections between everyday actions and the mechanisms associated with global climate change.

Embedded Assessment Responses

We analyzed students' unit responses following virtual investigations with NetLogo models that asked students to reason using evidence from the models to develop explanations about global climate change-related mechanisms. This analysis allowed us to detect progressions of change in students' ideas, examine reasoning and mechanistic understanding of key processes throughout the unit, and link changes in the key ideas to investigations with virtual models. Embedded assessments were analyzed in conjunction with post-unit interview responses to gain a more holistic understanding of students' ideas and sense making.

Case Studies

Based on interview analyses, an understanding of core mechanisms emerged as necessary in order for students to make connections between natural and anthropogenic mechanisms (e.g. understanding the greenhouse effect). Contrasting cases of one student (Carson) with complete, scientifically acceptable (i.e. normative) and one student (Justin) with non-normative understanding of the greenhouse effect. These students were in the same class and should have experienced the WISE curriculum in similar ways (though they each had a different partner throughout the unit). The case studies were descriptive and explanatory and used to track progressions of change throughout the unit (Yin 2009). The case studies allowed us to examine how differences in understanding of global climate change-related mechanisms developed over the course of the unit and impacted the connections these students made between everyday actions and increases in global temperature.

Results

Emergent Categories of Student Ideas

Students hold a wide range of ideas about the mechanisms that drive global climate change. When asked to describe mechanisms associated with increases in global temperature (i.e. warming mechanisms), the coders identified two main categories of warming mechanisms: anthropogenic and natural. The most common ideas fell into anthropogenic categories: those related to pollution (both human created—general—and those specific to energy use) and ozone (how human actions impact ozone). Students rarely cited natural processes/warming mechanisms. Students' incoming ideas represent a range of understandings to build on, distinguish, and challenge through instruction and interaction with models in the GCC unit. In addition, students obtain their ideas from a variety of evidence sources with science class, parents/relatives, and media among the top sources.

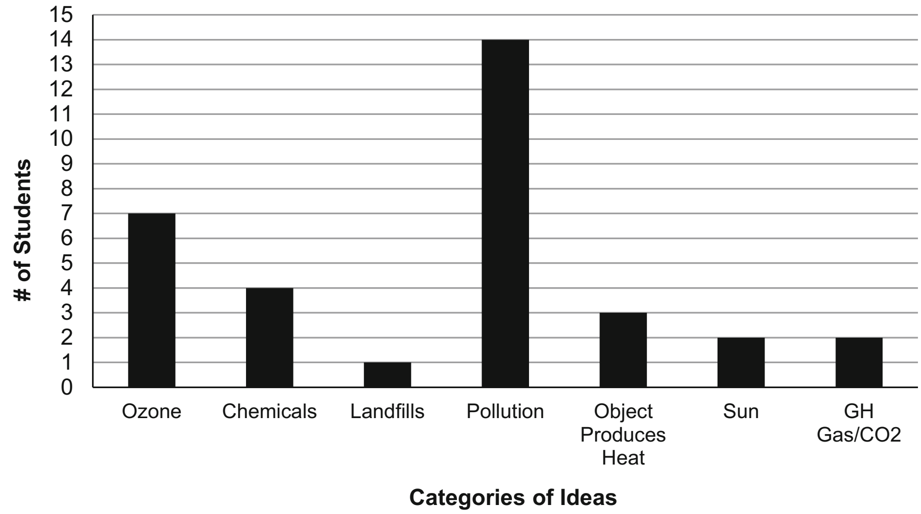

Fig. 2 Pre-unit ideas about the mechanisms associated with global climate change

Students' Incoming Ideas: A Focus on Anthropogenic Mechanisms

During pre-unit interviews, students were asked a variety of questions about global climate change-related mechanisms and increases in global temperature. Seven categories of global climate change-related mechanisms (i.e. warming mechanisms) emerged during pre-unit interviews (see Fig. 2; Table 1). These ideas fell into two main categories of mechanisms: (1) anthropogenic processes: general human actions (e.g. landfills) that students felt contributed to increases in warming and those specific to energy use (e.g. energy-related objects produce heat) and (2) natural processes: earth's natural warming mechanisms (e.g. greenhouse effect). The most common ideas fell into the anthropogenic categories. Interestingly, students rarely cited natural processes that warm the earth during pre-unit interviews. Students focused on human causes of global climate change, but not the mechanisms that warmed the earth naturally or how these natural mechanisms might be enhanced by human actions. As a result, students did not make connections between natural and anthropogenic mechanisms during pre-unit interviews.

It is important to note that warming mechanism categories *pollution* and *ozone* contain multiple subcategories (see Table 1). For ozone, all subcategories of ideas involve how human actions impact the ozone layer and therefore these ideas are included as anthropogenic processes. There is overlap among some subcategories. For example, a subcategory within ozone contains ideas about pollution (e.g. energy-use-related products destroy ozone). However, this idea is included with ozone when we combine all ideas associated with this category.

Students' Ideas Represent a Range of Understanding

Students' ideas within each of the seven warming mechanism categories represent a range of understanding. In addition, students often cited multiple and sometimes conflicting categories of ideas. The majority of students' ideas represent partial understandings (a combination of scientifically acceptable and incomplete or alternative ideas). Partial ideas represent ideas to build on and help students refine and distinguish throughout the unit. For example, Allen describes his understanding of how carbon dioxide is related to warming (i.e. see Table 1: Greenhouse gases/CO_2):

> CO_2, I think, lets the sunlight in, but it helps like the light get in but once it's in it can't get back out…. When it tries to bounce back out, it doesn't work, because maybe the sun, maybe the CO_2 is just pointing downward or something.

Here, Allen illustrates a partial understanding. The ideas that CO_2 lets sunlight in and points down are scientifically inaccurate, while the idea that sunlight can not "bounce back out" is incomplete yet accurate. A goal of the unit is to help students distinguish partial understandings.

Many of the ideas that emerged represent alternative understandings (scientifically inaccurate conceptions). Alternative ideas represent ideas to challenge through interaction with the unit. Some ideas in the alternative category are scientifically inaccurate ideas about natural processes or anthropogenic impacts on natural phenomena (e.g. see Table 1: Ozone). For example, Becca describes her ideas about how the sun relates to increase in temperature (i.e. see Table 1: Sun): "Well the sun is maybe getting hotter". This represents an alternative and scientifically inaccurate idea about the role of the sun in global climate change-related mechanisms. Other alternative ideas such as energy-related objects produce heat (e.g. light bulbs) are grounded in everyday experiences and accurate on a local level, yet do not contribute to increases in temperature on a global level and therefore represent an issue of scale.

Students often cited multiple categories of ideas that ranged in understanding. The range of understandings and dynamic interaction of ideas among categories illustrates the complexity of students' sense making around the mechanisms associated with global climate change.

Common Ideas: Pollution and Ozone-Related Mechanisms

The most common ideas that emerged during pre-unit interviews involved pollution and ozone (see Fig. 2). Subcategories of ideas within each of these larger mechanism categories represent a range of ideas to build on, distinguish, and challenge through interaction with the GCC unit (see Table 1).

Pollution-Related Mechanisms

Fourteen of the 15 students mentioned at least one warming mechanism involving pollution (see Fig. 2). Students discussed pollution in four main ways: (1) pollution: clouds/atmosphere (i.e. partial idea), (2) pollution: general (i.e. partial idea), (3) energy process creates pollution (i.e. partial idea), and (4) pollution is warm (i.e. alternative) (see Fig. 3).

The most common ideas about pollution involve mechanisms specifically associated with energy use (see Fig. 3). Approximately half of the students cited ideas in two energy-use-specific subcategories of pollution: (1) *pollution is warm* ($n = 7$) and (2) *energy process creates pollution* ($n = 8$) (see Fig. 3). Students' ideas that demonstrated the notion that energy use is literally warm were categorized as *energy-related pollution is warm*. Though these ideas were often grounded in everyday experiences at a local level, they are scientifically inaccurate on a global scale. Therefore, these ideas represent alternative conceptions. Many students discussed exhaust from cars as being warm; such ideas were coded as *pollution is warm*. Gina provides an example:

> I don't know but a long time ago my dad got a car, there was kind of smoke coming out of the car and it was really hot….I saw a car when it started like I was in the back and I saw this kind of smoke coming out of the car. So every car that I see pass by, I see that coming out. And when I pass by it's really hot.

Here, Gina reasons that the "smoke" coming from a car is hot, and because there are a lot of cars, this "smoke" could lead to increase in global temperature.

Students who cited ideas categorized as *energy process creates pollution* discussed how producing energy creates pollution (e.g. factories) in ways that contribute to increases in global temperature. These ideas, coded as *energy process creates pollution,* represent complete or partial understandings to build on throughout the unit. For example, though the energy process does create pollution, the goal of unit is to distinguish the types of pollution that contribute to changes in global temperature (e.g. green house gases) and the mechanisms involved (e.g. enhanced greenhouse effect). Some students discussed ways that the energy process creates pollution resulting in increases in global temperature. For example, Anna describes her ideas about how the process of making energy produces pollution:

> I think we get most of our electricity by burning coal… like energy, if coal was used, the burning of coal would, like it would emit a lot of pollution into

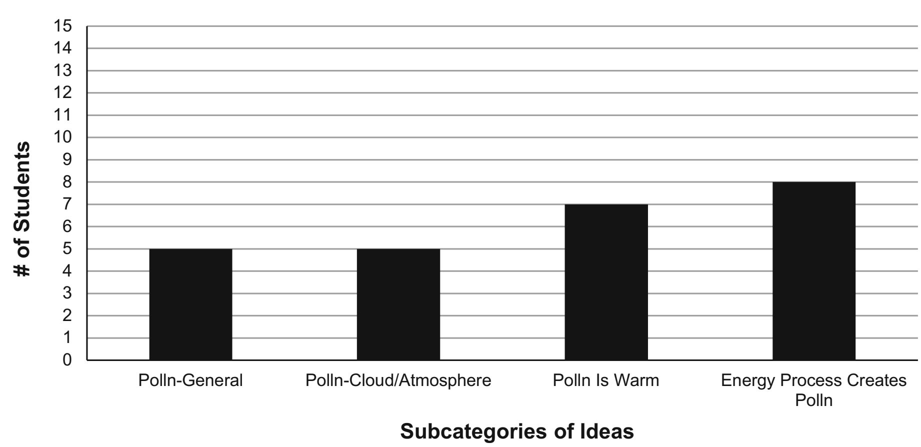

Fig. 3 Pre-unit pollution-related mechanism subcategories. The majority of students cited multiple subcategories of ideas within a main category. Exploration of subcategories reflects a larger number of individuals than those in Fig. 2 because individuals were counted once within the main category even if they cited multiple subcategories

> the air… there's not that much coal in the earth anymore and more pollution is going into the air.

Here, Anna attributes the burning of coal to the production of pollution. However, she does not discuss a specific mechanism for how pollution relates to an increase in global temperature. Therefore, Anna's ideas represent a partial conception.

Ozone-Related Ideas to Challenge

The second most common category of ideas about increases in global temperature involved ozone-related mechanisms. When broken into subcategories, two types of ideas emerge: (1) ozone holes (general): Holes in the ozone are letting more sunlight in causing increases in global temperature and (2) Energy-use-related products destroy ozone/get trapped: Products related to energy use destroy the ozone layer or get trapped inside of it causing an increase in temperature (see Table 1). The subcategories within ozone represent alternative conceptions to be challenged and distinguished throughout the unit.

The most common ozone-related mechanisms involve the destruction of ozone by pollution specifically related to energy use ($n = 5$) followed closely by ozone holes ($n = 4$). Some students linked pollution created from actions involving energy use (e.g. car exhaust) or the burning of fossil fuels to the destruction of the ozone layer. Anna, the student from above, provides an example. She extends her ideas about the burning of coal emitting pollution into the air:

> Well, I think that when it (pollution) gets into the air it rises because if its smoke…cause its not heavy, so it would rise and then again with the ozone layer, it would either destroy it or thicken it…because I've seen so many things saying that it's getting destroyed, but it makes more sense that it's getting thicker.

Here, Anna reasons about whether the ozone is getting thicker or getting destroyed. She cites hearing evidence that the ozone is getting destroyed, but thinks that because "smoke" is rising it might make sense that the ozone is getting thicker—and therefore holding in more heat.

In summary, students cited a variety of warming mechanisms that represent a range of understanding. Most ideas represent partial or alternative understandings of global climate change-related mechanisms. The most commonly cited mechanisms were anthropogenic ideas: those related to pollution and ozone. The most common pollution-related ideas were those specifically related to energy use. Students rarely cited natural processes or how earth is warmed naturally. Therefore, the majority of students did not make links between energy use and acceleration of natural processes during pre-unit interviews.

Students Obtain Ideas from a Variety of Evidence Sources

Students draw from a variety of evidence sources to support their ideas about global climate change-related mechanisms that should be considered when designing instruction (see Fig. 4). Science class was the most

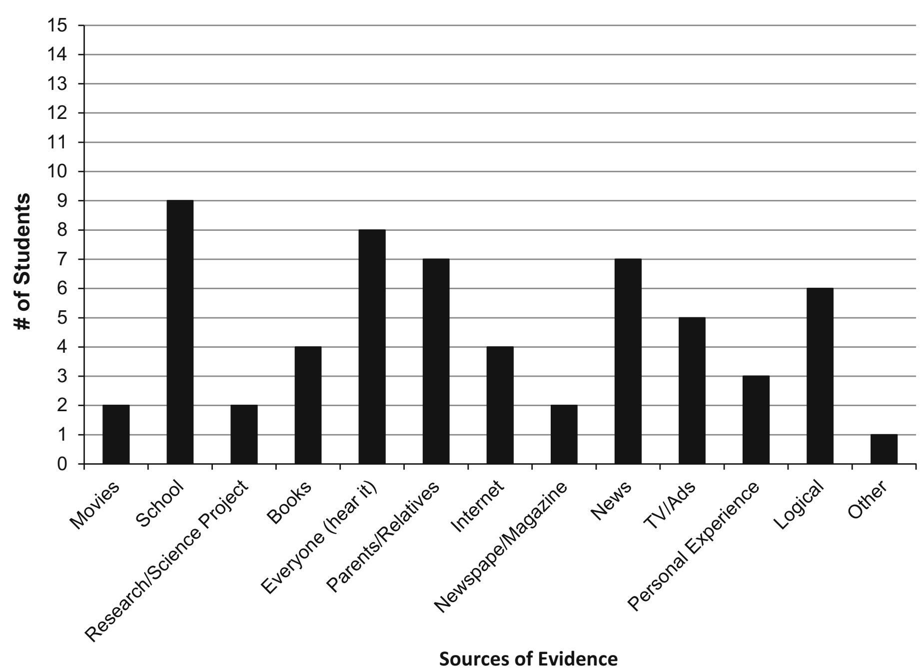

Fig. 4 Sources of evidence cited by students for global climate change-related mechanisms

common source of evidence for global climate change-related mechanisms, followed by everyone (hearing it around), parents/relatives, and the news. Some students also cited logic as their source of evidence based on information they received from different places (e.g. science class, news). Depending on the accuracy of information from different sources, students may negotiate multiple and conflicting ideas about the causes and consequences of global climate change.

When teaching about this complex scientific phenomenon, it is important to both appreciate the range of ideas students may have regarding global climate change and the multiple sources of accurate and potentially inaccurate information they are drawing from to inform their repertoires of ideas and reasoning about this issue.

In summary, students hold a variety of ideas about the mechanisms associated with global climate change. The ideas represent a range of understanding with partial and alternative ideas most common. The majority of warming mechanisms cited were anthropogenic categories with pollution and ozone-related ideas the most common. The most common pollution-related ideas were those related to energy use. Students focused on human causes of global climate change, but not the mechanisms that warmed the earth naturally or how these natural mechanisms might be enhanced by human actions. As a result, students did not make connections between natural and anthropogenic mechanisms during pre-unit interviews. In addition, students cite a variety of evidence sources for their ideas about global climate change-related mechanisms.

Post-Unit Analysis

Ideas Added, Distinguished, and Persisted

Consistent with the knowledge integration framework, students added ideas during instruction. Interaction with the unit and investigation with NetLogo models helped students add scientifically acceptable ideas in both main mechanism categories: natural processes and anthropogenic (energy-use-specific). In addition, some students distinguished ideas about pollution through interaction with the unit. However, some alternative conceptions persisted following completion of the unit including ideas about ozone. The persistence of alternative ideas created challenges for some students to integrate their ideas and construct more coherent understanding.

The addition of ideas in both natural and anthropogenic mechanism categories allowed some students to make connections between everyday energy use and the enhancement of natural processes resulting in the acceleration of global temperature.

New Ideas Added During Unit: Natural and Anthropogenic Mechanisms

During post-unit interviews, three new ideas about natural mechanisms emerged: radiation transformation, greenhouse effect, and albedo (see Fig. 5; Table 1). These ideas represent complete (scientifically acceptable ideas) or partial understandings. In addition, one new idea regarding

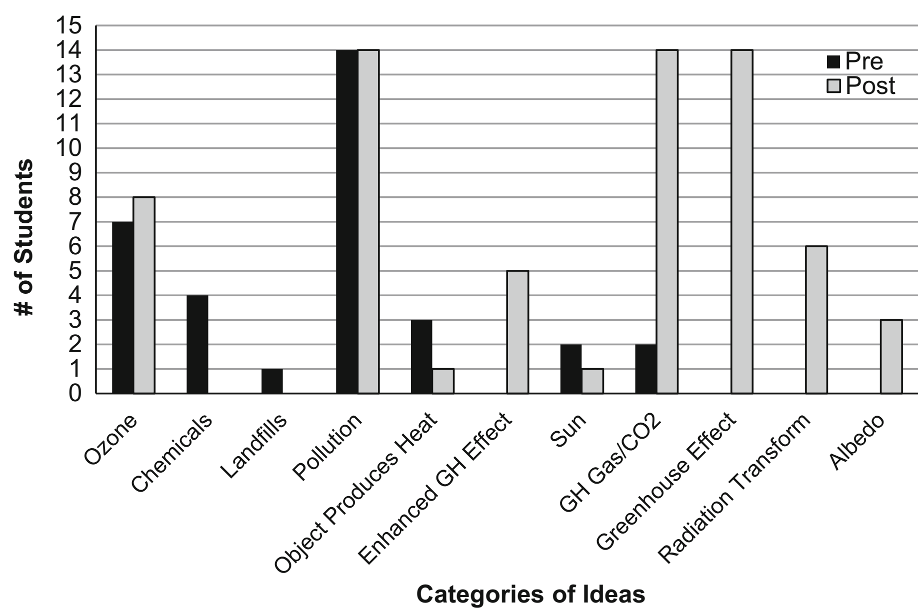

Fig. 5 Comparison of pre- and post-unit global climate change-related mechanisms cited by students

anthropogenic mechanisms specifically related to energy use emerged: enhanced greenhouse effect. This idea represents a complete understanding of how the natural greenhouse effect is enhanced by human actions involving energy use (see Fig. 5; Table 1). These categories of ideas represent core mechanisms addressed through NetLogo models in the unit.

In this section, we examine embedded assessments following virtual investigations with NetLogo models in order to better understand *how* new ideas were added to students' repertories during the unit. Implications for the development of complete (i.e. normative) versus partial (i.e. mixture of normative/non-normative) understandings in the new mechanism categories are discussed in the "Bridging" section that follows.

Ideas Added: Models Help Develop Understanding of Natural Mechanisms

During post-unit interviews, three new natural mechanisms emerged: radiation transformation, greenhouse effect, and albedo (see Fig. 5). During post-unit interviews, six of 15 students added a new idea and displayed a complete or partial understanding of the mechanisms associated with radiation transformation (see Fig. 5). Analysis of embedded assessments following investigations with the Radiation Transformation NetLogo model shows how interaction with models may have helped students develop an understanding of radiation transformation and add this idea to their repertories. During virtual investigation, students were able to add/remove sunrays, observe radiation transformations, and document changes in global temperature graphed in real time adjacent to the model. Following investigation, students were asked to explain how solar radiation changed in the model in an embedded assessment. Kelly is representative of the six students described above who added a complete/partial understanding of radiation transformation through interaction with the model. In an embedded assessment, Kelly and a student partner describe what they observed through their investigation:

> When the solar radiation hit the surface of the Earth, some of it reflected and some of it transformed into heat energy and moved around under the surface of the Earth. Then later it changed into infrared light and went into space.

This dyad describes a complete understanding of the mechanisms associated with the transformation of solar radiation to heat to infrared radiation. This suggests that the observations they made during their investigations while adding/removing sunrays and "watching a sunray" (i.e. a function allowing students to isolate an individual sun ray and observe its interactions) allowed Kelly to add a new idea (i.e. radiation transformation) as documented in the post-unit interview.

In addition, during post-unit interviews, 14 of 15 students added a new idea and displayed a complete or partial understanding of the mechanisms associated with the greenhouse effect (see Fig. 5). Analysis of embedded assessments following investigations with the Greenhouse Effect NetLogo model shows how interaction with models may have helped students develop this understanding. Students performed investigations by adding/removing greenhouse gases, observing the interaction of solar/infrared radiation and greenhouse gases, and documenting changes in global temperature graphed in real time adjacent to the model. Following investigations with the model, students responded to an embedded assessment where they explained what happens to solar and infrared radiation when it runs into a greenhouse gas.

Allen is representative of the 14 students described above who added a complete/partial understanding of the interaction of solar/infrared radiation with greenhouse gases as documented in the post-unit interview. He and his partner describe their understanding in an embedded assessment following their investigation with the model: "The greenhouse gases reflect the infrared radiation (IR) and let solar radiation in, so the IR stays and heats up the earth." Here, Allen and his partner show a complete understanding of the different interactions of solar and infrared radiation with greenhouse gases as well as how this impacts global temperature.

The addition of ideas about earth's natural mechanisms as documented in post-unit interviews, in combination with an analysis of embedded assessments following investigations with NetLogo models, shows how interactions with models may have helped students develop a mechanistic understanding of these important processes.

Ideas Added: Models Help Develop Understanding of Enhanced Greenhouse Effect

During post-unit interviews, a new anthropogenic mechanism emerged specifically related to human actions involving energy use: enhanced greenhouse effect. Five of 15 students cited this idea during post-unit interviews (see Fig. 5). This idea aligns with core mechanisms emphasized through virtual investigations/instruction during the unit and represents an increase in coherent understanding.

Embedded assessments following investigation with the Human Actions and Greenhouse Gases NetLogo models show that interaction with the models may have contributed to an understanding of how the natural greenhouse effect is enhanced by human actions involving energy use. During virtual investigations, students could add/remove greenhouse gases, observe interactions of greenhouse gases and infrared radiation, and document changes in global temperature graphed in real time. Allen, the student from above, is representative of the five students who added the idea of an enhanced greenhouse effect to their repertoires. In an embedded assessment following virtual investigations, Allen builds on his idea above that "greenhouse gases reflect IR" which "heats up the earth" (i.e. the greenhouse effect). In an embedded assessment following an investigation with the model, he and his partner state: "We burn fuel to make energy, and that produces green house gases." Here, Allen and his partner add ideas about the production and sources of greenhouse gases as a result of observations made during their investigations with models. Allen is then able to link these ideas to increases in global temperature during post-unit interviews. In a post-unit interview, he recounts the entire process:

> A: Because it's (solar radiation) not in the form of sunlight anymore, it's in the form of infrared radiation.. the heat is turning into IR, it's bouncing off the greenhouse gases back to earth, so it just gets warmer and warmer.
> Interviewer: Do you think there are things that people are doing that might be related to causing that to happen?
> A: Yeah. Driving cars, factories, burning coal, fuels…because, those things all emit CO_2 and that … contributes to greenhouse gases.

Here, Allen applies knowledge gained from the unit. He displays a complete understanding of the natural mechanisms associated with radiation transformations and the interaction of greenhouse gases and infrared radiation to how human actions involving energy use (e.g. burning fossil fuels) enhance these natural processes (i.e. the enhanced greenhouse effect).

The addition of ideas about the anthropogenic mechanism *enhanced greenhouse effect* is documented in post-unit interviews, as well as in an analysis of embedded assessments following investigations with NetLogo models. The assessments show how interactions with models can help some students develop a more sophisticated understanding of energy-related mechanisms and make connections between everyday energy use, the production of greenhouse gases, and how natural processes (e.g. greenhouse effect) are enhanced by these human activities.

Partial Ideas About Pollution Distinguished

During post-unit interviews, students distinguished general ideas about pollution and added ideas about the contribution of specific types of pollution to global climate change. Though the same number of individuals cited pollution pre and post ($n = 14$, see Fig. 5), significant shifts occurred in the types of pollution mechanisms cited from pre to post that represent more sophisticated understandings. As a result, the number of general ideas about pollution (pollution general, pollution clouds/atmosphere) decreased, while the percentage of ideas about greenhouse gases/carbon dioxide increased (see Fig. 5). Unlike pre-unit interviews where only a few students discussed greenhouse gases more generally ($n = 2$), during post-unit interviews the majority of students mentioned greenhouse gases ($n = 14$) and how greenhouse gases are produced by human actions involving energy use/the energy process (i.e. energy process creates pollution, $n = 10$). In addition, some students mentioned carbon dioxide as a specific type of greenhouse gas ($n = 8$). This indicates that some students distinguished and refined ideas from the unit about pollution to be more specific to the impact of greenhouse gases on increases in global temperature.

However, despite these refinements, several students retained the alternative conception that energy-related pollution is warm and the number of ideas in this category only decreased slightly from pre to post (see Fig. 5).

Alternative Conceptions Persisted: Ozone and Energy-Use-Related Mechanisms

While some students added and/or distinguished ideas about warming mechanisms based on interaction with the unit as discussed above, other students struggled to refine alternative conceptions involving ozone and energy use and did not develop more coherent arguments.

Overall, a greater number of students cited ozone during post-unit interviews ($n = 8$) compared with pre-unit interviews ($n = 7$) (see Fig. 5). During post-unit interviews, three students refined ideas about ozone and did not cite ozone-related mechanisms, while four students maintained ideas about ozone (either in the same subcategory or shifted subcategories). Interestingly, four new students added ideas about ozone during post-unit interviews. The majority of these new students (3/4) added ideas in the *energy-use-related products destroy ozone/gets trapped* subcategory. The findings show that some students add alternative conceptions about ozone, possibly when they get stuck and cannot connect ideas they have explored in the unit. They often connect these ideas to new ideas from the unit involving greenhouse gases and energy use. Thus, during post-unit interviews, four students made a connection between greenhouse gas production and depletion of the ozone layer (energy use destroys ozone). Maria provides an example:

> We use a lot of greenhouse gases like our cars and gas stoves and stuff….all the greenhouse gases are bad for the air, and when they reach the ozone layer,

make it thinner, and ozone protects us from suns ultraviolet rays.

Maria displays confusion about greenhouse gases—stating that they are “used” rather than produced (e.g. by cars). In addition, she makes a direct link between greenhouse gases and the destruction of the ozone layer leading to an increase in global temperature. This non-normative connection reflects a struggle to explain without sufficient information and underscores the importance of iterative refinement of curriculum materials to take account of students’ ideas.

The idea that energy use destroys ozone was not mentioned during instruction. Ideas about ozone were not challenged with evidence in the unit since they had not arisen in previous studies. The prevalence of this idea suggests that it was discussed in class or introduced in some other context. Embedded assessments following virtual investigations, described above, suggest that making observations during investigations may have allowed some students (e.g. Kelly, Allen) to effectively distinguish their ideas involving ozone. Students who retained or added ideas about ozone were unable to explore these alternative conceptions through virtual investigations and therefore were unable to gather empirical evidence to challenge these ideas. The emergence of this idea as a possible explanation illustrates the value of trial and refinement of instruction, especially for complex systems such as climate change.

In addition, while some students refined alternative conceptions that energy-related pollution is warm and contributes to an increase in global temperature, several students retained this idea ($n = 5$) during post-unit interviews.

In summary, analyses indicate that students added new ideas involving natural and anthropogenic mechanisms while studying the unit and performing investigations with NetLogo models. Analyses of post-unit interviews in conjunction with embedded assessments show how models may have helped students develop these understandings of natural and energy-use-specific mechanisms. The ozone idea needs to be addressed in revisions to the unit in order to guide students and to provide an opportunity to distinguish this idea.

Bridging Natural and Anthropogenic Mechanisms: Human Actions and Increasing Temperature

Students added ideas involving natural and anthropogenic mechanisms specific to energy use through interaction with the unit as discussed above. For the students interviewed, analyses reveal that developing a complete/normative understanding of particular natural mechanisms (e.g. radiation transformation, interaction of infrared radiation, and greenhouse gases) *and* an anthropogenic: energy-use-specific mechanism (e.g. enhanced greenhouse effect) is necessary for students to integrate their ideas about how human actions involving energy use relate to increases in global temperature. Results show that developing a complete/normative understanding of both types of mechanisms (natural *and* anthropogenic) is necessary in order for students to distinguish different types of environmental issues and determine why certain human actions contribute to increases in global temperature (e.g. driving cars) while others do not (e.g. littering).

Emergence of Core Conceptions: Natural and Energy-Use-Specific Mechanisms

Results show that for the students interviewed, developing a complete and normative understanding of two natural mechanisms: (1) transformations between solar and infrared radiation and (2) the interactions between infrared radiation and greenhouse gases, was critical for constructing a complete/normative understanding of a third natural mechanism: the greenhouse effect (see Table 2, left side). Note that the students with an “*X*” in italics developed a normative understanding of these mechanisms. Of the students interviewed, only those that developed a complete/normative understanding of these mechanisms constructed a complete normative understanding of the greenhouse effect (see Table 2, top 5 students).

In addition, analyses show that developing a complete/normative understanding of the greenhouse effect provides an important bridge that helps students integrate their ideas between natural and anthropogenic mechanisms (i.e. how human actions involving energy use enhance natural processes). Of the 15 students interviewed, only five students held complete/normative conceptions of the greenhouse effect following completion of the unit. These five students also held complete/normative conceptions of radiation transformations as well as the role of greenhouse gases (with the exception of one student) (see Table 2, left side, natural mechanisms). These are the only students interviewed who developed an understanding of the enhanced greenhouse effect (see Table 2, right side, anthropogenic mechanisms) and made connections between the natural and anthropogenic mechanisms. Therefore, for the students interviewed, developing a complete/normative understanding of the greenhouse effect was necessary for students to understand the enhanced greenhouse effect and how human actions involving energy use contribute to increases in global temperature.

Results show that the five students integrated their ideas about energy use and pollution with ideas about natural mechanisms (e.g. radiation transformation) throughout the unit in order to construct an understanding of the enhanced greenhouse effect. For example, during pre-unit interviews,

Table 2 Post-unit normative versus non-normative conceptions of natural and anthropogenic mechanisms

Student	Natural Mechanisms						Anthropogenic Mechanisms	
	Radiation Transformation		Greenhouse Gases and Infrared Radiation		Greenhouse Effect		Energy Process Creates Pollution	Enhanced Greenhouse Effect
	Normative	Non-norm	Normative	Non-norm	Normative	Non-norm	Normative	Normative
A	*X*		*X*		*X*		*X*	*X*
Z	*X*		*X*	X	*X*		*X*	*X*
KR	*X*		*X*		*X*		*X*	*X*
C	***X***		***X***		***X***		***X***	***X***
KA	*X*		*X*		*X*		*X*	*X*
G		X		X		X	*X*	
JI	*X*			X		X		
B		X		X		X	*X*	
J		**X**	*X*	**X**		**X**	***X***	
K		X		X		X	*X*	
M		X		X		X		
BC		X	*X*	X		X		
MI		X		X		X		
GA		X	*X*			X		
D		X	*X*			X	*X*	

Case study Justin (J) and Carson (C) in bold and bold italics. Italics = normative conceptions

three of these students made links between places where energy is made (e.g. factories), processes (e.g. burning coal), and products (e.g. pollution). During post-unit interviews, these students further integrated their ideas with new ideas from the unit stating that infrared radiation reflects off of greenhouse gases produced from burning coal. In this way, students were able to integrate natural and anthropogenic mechanisms to develop an understanding of the enhanced greenhouse effect.

Mechanistic Understanding: Impact on Advice for Lowering Energy Use

Embedded assessments following virtual investigation with NetLogo models involving different types of energy use show that the five students who bridged ideas between natural and anthropogenic mechanisms developed a more coherent understanding about how some actions relate to greenhouse gas production/an increase in global temperature while others do not. This impacted students' understanding of *how* advice given to lower one's energy use would make a difference.

Results show that developing an understanding of the specific mechanisms associated with natural processes (e.g. radiation transformation) allows students to integrate their ideas and develop a complete/normative understanding of anthropogenic mechanisms. The five students who developed a complete/normative understanding of the natural and anthropogenic mechanisms described above also more successfully described the specific mechanisms associated with these processes.

Findings show that differences in mechanistic understanding impacts students' comprehension of *how* their advice for lowering one's energy use would impact global temperature. For example, Allen (the student from above) and Jill are both students in the same classroom. Allen is representative of the five students who developed a complete/normative understanding of the natural and anthropogenic mechanisms described above as displayed during post-unit interviews. Jill is representative of those who did not develop this understanding (see Table 2, students "A" and "JI"). At the end of the unit, students used NetLogo models to test predictions about how different human actions (e.g. walking to school vs. riding in a car) impact greenhouse gas production and global temperature. Students were then asked to offer advice to a friend for how to best lower energy use and to explain why this action would make a difference. Jill, Allen, and their partners offer the same advice for lowering energy use following investigations with models: walk to school instead of riding in a car. In an embedded assessment following investigations, students were asked to describe how this action relates to the amount of greenhouse gases produced. Jill and her partner state: "They don't relate at all. Greenhouse gases are totally different." Allen and his partner display a different understanding: "Because it (walking) doesn't really produce CO_2 like driving in cars." Here, Jill and her partner do not make connections between different human actions and the production of greenhouse gases, while Allen and his partner do. Like Allen, the five students who described mechanisms for how actions involving energy use relate to greenhouse gas production more successfully made links between actions and production of greenhouse gases.

Building on this, an additional embedded assessment asked students how the action they selected for lowering energy use (in this case: walking instead of driving) impacts global temperature. Jill and her partner explain: "Car fuel goes into the air and it's so dirty that it hurts the earth." Allen and his partner again display a different understanding: "Then the IR (infrared radiation) would bounce off less green house gases so the temperature wouldn't rise so fast." Combining this with their ideas from above, Allen and his partner state walking produces less CO_2 and therefore there would be a smaller quantity of greenhouse gases for infrared radiation to bounce off, while Jill and her partner attribute car fuel to a general view that greenhouse gases are harming the environment.

This example illustrates that students who used models to develop mechanistic understanding of anthropogenic activities were more able to make connections between actions, products, and outcomes. This has implications for students' abilities to understand how human actions impact global temperature. It also has implications for students' ability to create innovative solutions to reduce human activities that enhance climate change. An understanding of natural *and* anthropogenic mechanisms allows students to integrate ideas and determine how actions relate to changes in global temperature and what humans can do to make a difference.

In summary, analyses reveal that developing a complete/normative understanding of natural *and* anthropogenic mechanisms is necessary for students to integrate their ideas about how human actions involving energy use relate to increases in global temperature. New ideas added about natural processes (e.g. radiation transformation, interaction of greenhouse gases and infrared radiation) created a bridge between natural processes and anthropogenic mechanisms. This allowed students to develop an understanding of how energy use relates to increases in global temperature through the enhancement of natural processes (e.g. the enhanced greenhouse effect). A complete/normative understanding required students to understand the specific mechanisms involved with these core processes. This is important because it impacts students' understanding of *how* advice for lowering one's energy use would make a difference. Investigations with models can help with mechanistic understanding of core processes.

Examples of how these multiple, sometimes conflicting ideas evolve throughout the unit are illustrated in the case study of Justin and Carson below.

Case Study of Justin and Carson

The following cases are representative of two groups of students discussed above—those that developed a normative understanding of the greenhouse effect and made connections to natural and anthropogenic mechanisms involving everyday energy use (i.e. enhanced greenhouse effect) (e.g. Carson) and those that did not (e.g. Justin) [see Table 2, Carson (C) and Justin (J) are indicated in bold]. Justin is representative of students who added to and/or retained alternative ideas within their repertoires and did not integrate their ideas throughout the unit. Carson is representative of students who revised alternative understandings and integrated their ideas based on interaction with the unit.

Pre- vs. Post-Unit Ideas

During pre-unit interviews, Justin cited a mixture of partial and alternative conceptions about why global temperature might increase, while Carson cited two alternative conceptions (see Table 3). Both students cited the same alternative conceptions regarding the role of ozone in increasing global temperature (see Table 3). During post-unit interviews, the ideas Justin and Carson described regarding the core natural mechanisms discussed above indicate that important differences occurred in the

Table 3 Pre- and post-warming mechanisms cited by Justin (J) and Carson (C)

Warming Mechanism	Pre	Post
Anthropogenic Mechanisms		
Ozone	J, C	***J***
Pollution		
General/clouds/atmosphere	J	
Is warm	C	
Created by energy process	J, C	J, C
Landfills		
Chemicals		
Energy object produces heat		
Enhanced greenhouse effect		***C***
Natural Mechanisms		
Sun		
Greenhouse gases		***J (non-norm/normative)***
Carbon dioxide (CO_2)		***C (normative)***
Albedo		J, C
Greenhouse effect		***J (non-normative)***
		C (normative)
Radiation transformation		***C (normative)***

Note Important differences in bold italics development of their ideas throughout the unit. Carson developed a complete (i.e. normative) understanding of the core mechanisms: radiation transformation, greenhouse gases, and greenhouse effect, while Justin developed partial or alternative understandings in all categories (see Table 2, 3). This impacted Justin's ability to integrate his ideas involving natural and anthropogenic warming mechanisms. Though Justin maintained and added ideas about how the energy process creates pollution throughout the unit, he did not develop a normative understanding of the enhanced greenhouse effect. In addition, Justin maintained his alternative conception about ozone but shifted this conception to energy use destroys ozone, while Carson refined this idea through interaction with the unit.

Analysis of embedded assessments for Justin and Carson following virtual investigations with NetLogo models for the three core natural mechanisms (radiation transformations, role of greenhouse gases, and the greenhouse effect) reveals how differences in constructing a complete/normative conception of the greenhouse effect developed (see Table 3). In addition, the analysis shows how these differences impacted the connections Justin and Carson made between anthropogenic mechanisms involving everyday energy use and the enhancement of natural processes (e.g. enhanced greenhouse effect).

Differences in Understanding Radiation Transformations

Embedded assessments for Justin and Carson following virtual investigations with the Radiation Transformation NetLogo model illustrate how the ability to extract information from the NetLogo model led to differences in understanding of radiation and transformations of energy. Following completion of the unit, Carson holds a complete/normative conception of radiation transformation, while Justin does not (see Table 2, "radiation transformation," far left columns).

During the unit, students conducted virtual investigations involving the radiation transformation process: sunrays hit earth, are absorbed, turn into heat, and exit as infrared radiation. Following interaction with the model, students were asked to explain how solar radiation changed or transformed in the model. Justin, Carson, and their respective partners responded as follows:

> J: Solar radiation changed and transformed by bouncing off the surface of Earth or being absorbed by the surface of Earth.
> C: Solar radiation is changed into thermal heat if it is absorbed into the Earth. It is transformed into infrared radiation and released out of the Earth.

Justin and his partner state that solar radiation is "transformed" but do not specify outcomes for these transformations (i.e. production of heat/infrared radiation). However, Carson and his partner describe how solar radiation changes to heat and is transformed into infrared radiation (IR). This results in differences in what Justin and Carson recall about solar radiation and IR during post-unit interviews:

> J: I know (IR) it's a type of radiation, I don't think it's as harmful as UV radiation.
> C: It showed in the models, the sunlight, the little yellow arrows got absorbed. They were little yellow balls in the ground and they would bounce around and eventually released as IR rays with purple arrows.

As a result of his careful observations and in-depth exploration of the model, Carson recalls the specific mechanisms and types of radiation transformations that occurred while Justin recalls general information. This results in the development of differential understandings of what solar and infrared radiation are and how radiation transformations take place. This finding underscores the importance of promoting in-depth engagement with NetLogo models in order for students to distinguish existing ideas and incorporate new ideas from the unit into their repertoires.

Confusion About Role of Greenhouse Gases

Following completion of the unit, Carson holds a complete/normative conception about the role of greenhouse gases, while Justin has an incomplete understanding comprised of normative and non-normative ideas (see Table 2, "greenhouse gases," middle columns). During the unit, students conduct virtual investigations involving the function of greenhouse gases and how the addition/removal of these gases impacts global temperature. Following exploration of the model, students explain how solar radiation and IR interact with greenhouse gases and affect temperature. By documenting each transformation during the virtual investigation through detailed observations, Carson could explain what happens and *why* it happens when solar radiation and IR encounter greenhouse gases.

Following an investigation with the model, Justin displays an understanding that IR bounces off of greenhouse gases and that the presence of greenhouse gases causes an increase in global temperature. In an embedded assessment following an investigation with the model, Justin and his partner state:

> From what we have observed we are confident that IR is reflected off the greenhouse gas, SR (solar radiation) goes right through, and greenhouse gases make Earth warmer because of the trapped heat energy underneath.

Justin and his partner say, "we observed" referring to their observations following virtual investigations with the models. Carson and his partner display this same understanding but make an important distinction between short and long wave radiation indicating a sophisticated understanding of the mechanisms involved:

> Greenhouse gases are transparent to solar or short wave radiation, but are opaque to IR or long wave radiation. The long wave radiation bounces off the greenhouse gases and stays in the atmosphere, making it warmer.

Later in the unit, students explore the carbon cycle and are asked to apply their understanding of greenhouse gases to this concept. In their embedded assessment explanations for why global temperature increases following investigations with models, Carson and his partner focus on the role of carbon dioxide (CO_2) as a greenhouse gas, while Justin and his partner invoke a superficial connection to ozone:

> J: All of the CO_2 in the atmosphere building up will affect our ozone and cause more UV rays to go through.
> C: Carbon dioxide works as a greenhouse gas so the planet will heat up.

Justin and his partner do not incorporate the mechanisms associated with radiation transformation into their explanation and therefore do not describe how interactions between IR and greenhouse gases cause an increase in global temperature. Likewise, it is unclear whether this dyad understands that CO_2 is a type of greenhouse gas since they do not seem to extend their understanding about the function of greenhouse gases to CO_2. Finally, this finding in combination with the larger pool of interviewees that retained or added the idea of ozone in the post-unit analyses above suggests that instruction should address alternative conceptions about the ozone layer directly.

Conceptions of the Greenhouse Effect

Not surprisingly, differences in understanding of radiation transformations and the role of greenhouse gases results in differential understanding of the greenhouse effect. Examination of post-unit interviews and embedded assessments show that Carson displays a complete/normative understanding of the greenhouse effect, while Justin holds an incomplete understanding containing both normative and non-normative ideas (see Table 2, "greenhouse effect," far right columns). During post-unit interviews, Carson revises alternative conceptions about ozone and *pollution is warm* due to careful observations made during his virtual investigations with the NetLogo models (see Table 3). This allows him to develop a sophisticated understanding of transformations from solar radiation to IR and the role of greenhouse gases. He displays a normative understanding of the greenhouse effect:

> Solar radiation, when it comes down, some of it reflects off the atmosphere and some of it keeps going and the clouds reflect some of it …it might get reflected by the ground depending on the kind of albedo, that the ground has… and the stuff that gets absorbed, …eventually they would be released as IR rays. And some of the greenhouse gases reflected it back if there was a lot of greenhouse gas.

As mentioned above, Justin adds ideas from the unit, but gains a more superficial understanding that does not permit him to develop a complete explanation of the greenhouse effect:

> I think it has something to do with greenhouse gases being trapped in our atmosphere. When they get through the ozone they get trapped inside making the earth warmer.

Similar to Justin, ozone-related energy mechanisms remained persistent in post-unit interviews for some students. The same number of students cited ozone-related mechanisms in pre- and post-unit interviews ($n = 7$), though surprisingly, only three of these students were the same from pre to post (e.g. Justin). Therefore, four students revised their ideas about ozone (e.g. Carson), while four others added this non-normative idea to their existing repertoires.

Making Connections Between Natural and Anthropogenic Mechanisms

Like Carson, only students who held complete/normative conceptions of the greenhouse effect made connections between everyday energy use and the human-induced acceleration of global temperature (i.e. enhanced greenhouse effect) (see Table 2). The same five students who held complete/normative understandings of the greenhouse effect above were the only students who made connections between energy use, greenhouse gas production, and interaction with IR. As a result of this integration of ideas, these five students were the only students to site greenhouse effect as a warming mechanism and enhanced greenhouse effect as an energy-related mechanism during post-unit interviews (see Table 2).

Carson provides an example from the group of five students who integrates ideas in this way as illustrated in the following statement from his post-unit interview:

> If you use a lot of electricity…the people making electricity have to burn a lot more coal and the more coal you burn the more CO_2 and other gases, greenhouse gases it puts out into the atmosphere, so the infrared radiation stays in the atmosphere and warms the planet.

As a result of in-depth engagement with the NetLogo models, Carson applied his complete/normative understanding of the greenhouse effect to his understanding of anthropogenic: energy-related mechanisms. He then incorporated new ideas about how energy use relates to increases in global temperature into his repertoire (see Table 3).

Students who were unable to integrate their ideas made incomplete connections between everyday energy use and increases in global temperature. These ideas were not sufficient to fully explain human contributions to climate change. Some students connected energy use and the creation of pollution/greenhouse gases (i.e. energy process creates pollution) but did not extend this understanding to explain warming mechanisms.

Justin represents the group of students who recognize that energy use and greenhouse gas production are related but lack a full mechanism. He combines ideas about how cars produce greenhouse gases with alternative conceptions about greenhouse gases destroying the ozone layer (see Table 3):

> Cars are releasing gases into our atmosphere, the gases are hurting the ozone layer…Maybe it's like thinning the ozone so more sunlight can come in but can't get out.

He goes on to discuss how this relates to increases in global temperature:

> Maybe the gases hurt the ozone and make it thinner, so harmful sunlight is coming through and staying here, melting ice burgs and heating up the earth.

In summary, this analysis indicates that a normative understanding of two critical warming mechanisms: (1) transformation of solar to infrared radiation and (2) interaction of greenhouse gases and IR, is necessary for constructing a complete normative understanding of a third critical warming mechanism, the greenhouse effect. Though we cannot generalize findings with a small sample size, findings show that in this case a normative understanding of the greenhouse effect provides an essential bridge that allows students to integrate their ideas about everyday energy use with the warming mechanisms associated with global climate change.

These results and especially the case studies of Justin and Carson highlight the role and importance of models for fostering a sophisticated understanding of mechanisms in GCC. Thus, to understand transformations from solar to infrared radiation and the interaction of infrared radiation and greenhouse gases, students need to explore the model. Carson developed a complex understanding of these fundamental concepts through careful observations during virtual investigations with the NetLogo models. A complete/normative understanding of radiation transformations allows students to build more complex understanding of how radiation interacts with greenhouse gases in ways that may challenge alternative conceptions involving warming mechanisms. The same level of complete/normative understanding of the greenhouse effect is critical in order for students to make connections between warming mechanisms and everyday energy use.

Discussion

Findings from this study support and extend previous research on students' conceptions of global climate change. Findings show that developing a complete/normative understanding of natural *and* anthropogenic mechanisms is necessary for students to integrate their ideas about how human actions involving energy use relate to increases in global temperature. For the students in this study, developing a complete/normative understanding of the natural mechanisms described above (e.g. radiation transformation, interaction of infrared radiation and greenhouse gases) was foundational for developing an understanding of the greenhouse effect. Furthermore, developing a complete/normative understanding of the greenhouse effect was necessary for students to understand the enhanced greenhouse effect (an energy-use-specific mechanism) and how human actions involving energy use contribute to increases in global temperature. In addition, developing a complete/normative understanding required students to understand the specific mechanisms involved with these core processes. This is important because it impacts students' understanding of *how* advice for lowering energy use would affect global temperature. This has implications for students' abilities to develop innovative solutions to pressing issues of global climate change.

The analyses of embedded assessments and case studies illustrate how varying levels of engagement with models, including detailed observations of key transformations, leads to differences in the ways students integrate core ideas from GCC with ideas from their existing repertoires. This ultimately leads to the development of differential understanding of core mechanisms found to be essential in order for the students in this study to make connections between everyday energy use and increases in global temperature. The following discussion explores how enhancements to model-based instruction designed from the knowledge integration perspective can improve the design of GCC curriculum (Linn 2006) by more effectively promoting understanding of specific mechanisms associated with the core natural and anthropogenic processes highlighted in this study. First, we explore the overall findings for the ways student add, sort, and revise ideas. We then apply these findings to make recommendations for how to improve model-based instruction for specific core global climate change-related mechanisms.

Findings from the pre- and post-unit interviews document that students hold multiple and complex ideas about global climate change-related mechanisms. From the knowledge integration perspective, students add, distinguish, and reflect on ideas in the following ways: (1) adding ideas: findings show that some students (e.g. Allen, Kelly, Carson) added ideas from the unit through detailed exploration of the models in order to develop robust understanding of core GCC mechanisms and concepts; (2) distinguishing ideas: some students engaged with the models in ways that allowed them to distinguish between productive and non-productive ideas and resolve conflicts within their repertoires. Students who took a more superficial approach to the models were unable to distinguish among conflicting ideas and only developed partial understanding of core mechanisms. These students need additional guidance to interpret the models; and (3) reflecting: students who were able to reflect back on initial/incoming alternative conceptions and evaluate these ideas in relation to new content from the unit/models successfully resolved conflicts within their repertoires (e.g. Carson revised his initial ideas about ozone). Those students who developed only partial understanding of core mechanisms were unable to integrate their ideas in this manner. These results underscore the importance of providing instruction that allows students to gain insight into the mechanisms governing complex systems. Accurate models are not sufficient. Students need more guidance to help them recognize how the system works.

Next, we make recommendations for how to improve model-based instruction for key global climate change-related mechanisms.

Radiation Transformations

Findings show that a complete/normative understanding of the specific mechanisms associated with radiation transformations proved to be an essential foundation for building further understanding. Confusion about what solar and infrared radiation are, and if/how they are different remained common among the students interviewed. This coincides with previous work in this area that found that students do not distinguish different types of radiation involved with the greenhouse effect (Osterlind 2005; Shepardson et al. 2009). In addition, the difficulty students had with understanding the transformation of solar radiation, to heat energy, to IR aligns with findings from earlier versions of GCC (Varma and Linn 2012).

However, findings show that deep engagement with models through careful observations during virtual investigations allows for the development of a complex understanding of the different types/forms of radiation and how solar radiation transforms to IR. Related research on the same version of GCC used in this study shows that the inclusion of pivotal cases such as isolating and watching a sunray can improve comprehension (Svihla 2012). This is illustrated by Carson whose careful observations led to a normative understanding of different types of radiation and related transformations.

Implications for Model and Instructional Design

There are several features included in the radiation transformation model used in this study that are intended to help students develop a complex understanding of radiation transformations. These features include: (1) making visible unseen/unobservable phenomena, (2) inclusion of pivotal cases: the option to "watch" a sunray that isolates a single object and allows for focus within a complex modeling environment (Svihla 2012), (3) the option to slow down the model in order to make careful observations of the pathway that a sunray takes from the atmosphere to earth and back, and (4) the option to test variables (e.g. adding more sunrays) and explore the impact of different variables on global temperature.

While previous research shows that inclusion of careful observations in the form of pivotal cases (i.e. watching a sun ray as it enters earth, transforms to heat and then infrared radiation) improves comprehension of radiation transformations for students, results here suggest that the majority of students did not gain an understanding of the specific mechanisms involved from the model or did not retain this understanding long enough to integrate these ideas with those about energy use. Guidance that could promote more effective mechanistic understanding includes: (1) prompt students who have difficulty with the transformation of sunrays to predict what happens to a sunray as it leaves the atmosphere and enters earth and then test their prediction by following a sunray; (2) require students to record observations describing the pathway of a sunray and document each transformation in a virtual laboratory notebook. Ask students to classify the path of the sunray and describe the variety of paths that sunrays can follow. This will allow students to add productive ideas from the unit and provide data with which to revise existing alternative conceptions during reflection questions; (3) guide students to add details to their observations by slowing down the simulation; (4) guide students to isolate variables rather than changing several at a time (Varma and Linn 2012); finally, (5) encourage students who have incomplete ideas to reflect on the information they have recorded in their notebooks and revise their explanations.

In addition, Russ et al. (2008) devised a coding scheme to assess mechanistic reasoning. Applying some aspects of their coding scheme to instructional design (e.g. set up conditions, properties of entities, chaining backward/forward) may help students gain an understanding of natural mechanisms such as radiation transformation.

Greenhouse Gases and the Greenhouse Effect

Findings show that following GCC, the addition and refinement of greenhouse gas-related ideas within student's repertoires are possible. After exposure to the curriculum, the majority of students added ideas to their repertoires about the role of greenhouse gases and specifically carbon dioxide in global climate change. In addition, two of the students interviewed refined alternative conceptions involving greenhouse gases/CO_2 existing as an invisible layer from pre- to post-unit interviews. These students gained a normative understanding of greenhouse gases following instruction. However, similar to previous research, some students obtained only partial understanding of the greenhouse effect (Varma and Linn 2012).

Implications for Model and Instructional Design

The greenhouse gas and greenhouse effect models have potential for helping students develop complex understanding of these foundational concepts. These features include: (1) exploring sources/production of greenhouse gases, (2) examining the interaction of greenhouse gases and different types of radiation, (3) experimenting with adding/removing greenhouse gases to/from the atmosphere during virtual investigations, and (4) observing the impact of anthropogenic contributions to greenhouse gas production on global temperature graphed in real time alongside the model.

Suggested model-based instructional revisions to promote student engagement with greenhouse gas/effect models include: (1) prompt students to make more precise predictions about the interactions between greenhouse gases and IR and changes in global temperature, (2) guide students to record their observations about how different forms of radiation interact with greenhouse gases, (3) guide students to systematically vary greenhouse gas production and record changes in temperature, and (4) prompt students to reflect on the patterns they notice in their recorded temperature data. This will allow students to review their observational data, add and refine ideas, and write evidence-based explanations of *why* global temperature is increasing.

Connecting Everyday Energy Use and Increases in Global Temperature

Findings show that developing a complete/normative understanding of natural *and* anthropogenic mechanisms is necessary for students to integrate their ideas about how human actions involving energy use relate to increases in global temperature. Embedded assessments following virtual investigations with NetLogo models that illustrated the effect of different types of human actions associated with energy use revealed progress in understanding this complex area. Specifically, the five students who bridged ideas between natural and anthropogenic mechanisms (e.g. Allen, Carson) developed a more coherent understanding about how some actions relate to greenhouse gas production and result in an increase in global temperature. Other students did not make these connections (e.g. Jill, Justin). This understanding impacted students' understanding of how their advice for lowering energy use would make a difference.

Related research on the models used in this study found advantages for structuring investigations involving different human activities involving energy use in ways that restricted the problem space (e.g. contrasting activities in advance) (Svihla 2012). This promoted systematic student investigations and improved comprehension (Svihla 2012). However, similar to radiation transformation, findings in this study illustrate the challenges students have in integrating ideas about natural and anthropogenic mechanisms if they do not gain a complete/normative understanding of the mechanisms involved (e.g. enhanced greenhouse effect). In addition, consistent with other research, partial understanding leaves open the option to attribute production of car emissions to ozone layer depletion (Boyes and Stanisstreet 1997b). In addition, some students who gained only a partial understanding reverted back to their personal experiences of why temperature increases at the local level (e.g. car exhaust is warm) might increase temperature on a global scale.

Implications for Model and Instructional Design

Findings highlight how instruction can be improved to better use these modeling design features. Currently, instruction elicits students' ideas about everyday energy use and asks students to predict what types of actions have the greatest impact on global temperature. To more effectively help students negotiate their everyday experiences with energy use and increases in temperature at a global level, instructional revisions include: (1) allow students to test out how localized heat production (e.g. heat from a lamp) and larger scale production of energy (e.g. production of electricity to power the lamp) impact temperature increases at the global level. Prompt students to make observations and record temperature data so that they can analyze patterns in temperature data and construct evidence-based explanations, (2) make explicit and allow students to explore how energy is produced (e.g. electricity) and results in greenhouse gas production so students can add productive ideas to their repertoires, and (3) prompt students to reflect back on their ideas about greenhouse gas production, local versus global increases in temperature, and their recorded temperature data in order to facilitate connections between natural and anthropogenic mechanisms.

Finally, it is important to consider that students draw from a variety of evidence sources to support their ideas about global climate change-related mechanisms. Previous studies recommended that future work on global climate change should explore how the media and social interactions among peers, teachers, and parents influence the development of students' conceptions of global climate change (Shepardson et al. 2009). Findings from this study illustrate the importance of appreciating the range of ideas students have regarding global climate change and the multiple sources of accurate and potentially inaccurate information that they draw from to inform their ideas and reasoning about this complex issue. Findings from this study underscore the importance of eliciting students' ideas and providing instruction that allows students to fully distinguish ideas. Partial understanding is not sufficient to set students on a path to understanding. Full understanding is necessary to ensure that students are able to apply their ideas about mechanisms to create solutions for this complex issue.

Summary and Future Research

Findings show that developing a complete/normative understanding of particular natural mechanisms (e.g. radiation transformation, interaction of infrared radiation and greenhouse gases) *and* an anthropogenic: energy-use-specific mechanism (e.g. enhanced greenhouse effect) is necessary for students to integrate their ideas about how human actions involving energy use relate to increases in global temperature. This has implications for instructional design that aims to foster an understanding of the role of human activities in changes in global temperature and allows students to create innovative solutions to the complex problems of global climate change.

The features of the GCC NetLogo models are valuable for improving understanding but can only succeed when students are guided to gain understanding of the specific mechanisms involved and use the new ideas to integrate their understanding. Taking advantage of the design features of models and combining them with elements of the knowledge integration approach are essential to achieve integrated understanding. This approach will help students build fundamental understanding of the core mechanisms associated with global climate change and use the ideas in future situations. Model-based instruction that guides students to develop sophisticated mechanistic understanding has the potential to transform the teaching and learning of complex scientific phenomena such as global climate change.

Future research is needed to explore the types of strategies students use to conduct virtual investigations and how interaction with models most effectively engages students in evidence-based reasoning about global climate change-related mechanisms. In addition, research is needed that informs the refinement of model features and design of guidance that helps students develop productive strategies to make sense of the mechanisms involved. Finally, research is needed to clarify the modeling design features that challenge students to re-evaluate their prior understandings by using evidence from the unit.

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Appendix 1: Pre Unit Interview Protocol

1. Students' Conceptions of Global Climate Change: Elicit Ideas/Provide Access to Topic
    - Ecological Scenarios: Show picture that illustrates the consequences of global climate change (e.g. melting glaciers).
        - What do you think is happening in the picture?
            - Why? (Probe for description).
        - What other images come to mind?
            - Where did you hear about this/get these ideas?
    - Probe for causes of situation in picture:
        - What do you think is causing this to happen?

- What processes are taking place?
  - Scaffold hint structure for potential causes
    - Why is _x_ happening? What's causing it to happen?
    - How does _x_ make it warmer?
- Are there other things/processes that might be related to what you see here?
- Source of Ideas: Where did you get these ideas?

2. Reasoning: Mechanisms of Global Climate Change
   - Make Assertions: Natural and human actions causing increase in global temperature
     - Assertion example: "Some people say that all of the cars that people drive are warming the planet. Let's assume this is true."
       - Why would this be? (Probe for reasoning)
         - Allow students to construct narrative
       - How are (cars/natural processes etc.) related to the planet getting warmer? (Probe for reasoning)
         - Probe for mechanisms
   - Source of Ideas: Where did you get these ideas?
3. Reasoning: Energy Use
   - Elicit ideas about energy use:
     - In what ways do people use energy? (probe for examples)
     - What types of things you do at home that use energy? (probe for examples)
   - Show photos from Ecological Scenarios (above):
     - Do you think that this energy use is related to what's happening here?
       - Why or why not?
       - Why would using energy make it warmer?
   - Source of Ideas: Where did you get these ideas?
4. Advice: Lowering Energy Use
   - What suggestions do you have for the best things your friend can do to lower his/her energy use?
     - Why would this action reduce your friend's energy use?
       - Probe for mechanisms
     - Is this action related to global temperature? Why or why not?
       - If so, how?
   - Do you think it's important to try and save energy? Why or why?

Appendix 2: Post Unit Interview Protocol

1. Students' Conceptions of Global Climate Change: repeat questions for Pre Unit Interview (see Appendix 1)
2. Reasoning: Mechanisms of Global Climate Change: repeat questions for Pre Unit Interview (see Appendix 1)
3. Human Actions & Global Temperature: allow informed explanation from unit
   - During the unit you made a comparison of either: (1) eating meat versus littering or (2) driving vs. using electricity. Which comparison did you do? [*Select scenario based on response.*]
   - Scenario example: Turning off lights: "Jose's parents tell him to turn off his lights to save energy. He found out during the unit that he saves more energy by walking than turning off his lights. Jose doesn't think that leaving his lights on will have an impact on global temperature."
     - Do you agree with Jose—why or why not?
       - What evidence supports your ideas?
     - How is leaving lights on related to the planet getting warmer?
       - What evidence supports your ideas?
     - Probe for mechanisms of global climate change:
       - How is energy used to turn lights on?
       - Why would this increase global temperature?
       - What happens to solar radiation?
       - How is solar different from infrared radiation?
   - Source of Ideas: Where did you get these ideas/this evidence?
4. Ideas About Energy Use: repeat questions for Pre Unit Interview (see Appendix 1)
5. Advice: Lowering Energy Use: repeat questions for Pre Unit Interview (see Appendix 1)

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