

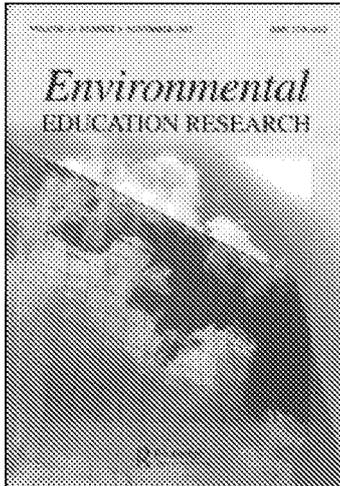
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Daniel P. Shepardson^{ab}; Soyoung Choi^a; Dev Niyogi^{bc}; Umarporn Charusombat^b

^a Department of Curriculum and Instruction, Purdue University, West Lafayette, USA ^b Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, USA ^c Department of Agronomy, Purdue University, West Lafayette, USA

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Seventh grade students' mental models of the greenhouse effect

Daniel P. Shepardson^{a,b,*}, Soyoung Choi^a, Dev Niyogi^{b,c} and Umarporn Charusombat^b

^a*Department of Curriculum and Instruction, Purdue University, West Lafayette, USA;*

^b*Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, USA;*

^c*Department of Agronomy, Purdue University, West Lafayette, USA*

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This constructivist study investigates 225 student drawings and explanations from three different schools in the midwest in the US, to identify seventh grade students' mental models of the greenhouse effect. Five distinct mental models were derived from an inductive analysis of the content of the students' drawings and explanations: Model 1, a 'greenhouse' for growing plants; Model 2, greenhouse gases cause ozone depletion or formation, causing the Earth to warm; Model 3, greenhouse gases, but no heating mechanism, simply gases in the atmosphere; Model 4, greenhouse gases 'trap' the sun's rays, heating the Earth; and Model 5, the sun's rays are 'bounced' or reflected back and forth between the Earth's surface and greenhouse gases, heating the Earth. Science textbooks are critiqued in light of the students' mental models and curricular and instructional implications are explored.

Keywords: climate change; conceptions; constructivism

Introduction

In 2007, the Intergovernmental Panel on Climate Change (IPCC) (2007) concluded that global warming is inevitable and that human activity is likely to be the main cause. However, a survey of the American public in the same year (ABC News 2007) reported that while 33% cited climate change as the world's top environmental issue, and 84% thought it was probably happening today, only 41% of the American public believed that global warming was caused by human activity. Furthermore, while 86% believed global warming would become a serious environmental problem if not corrected, 63% thought it could be reduced, with 62% claiming they knew a moderate amount about global warming. However, in a summary of US public opinion about global warming, Nisbet and Myers (2007) report that only 18% agree that every time we use coal or oil or gas, we contribute to the greenhouse effect.

While these findings suggest relatively few individuals in the US have adequate knowledge of the workings of the greenhouse effect, we understand them as underlining the importance of students learning about the greenhouse effect in order to understand the arguments and debates about the science of global warming and climate change. If science education is to both promote a citizenry that is knowledgeable about global warming and climate change, and one which can assume informed responsibility for the management and policymaking decisions facing our planet (Brown 1992;

*Corresponding author. Email: dshep@purdue.edu

Bybee 1993), then it is essential to identify students' mental models of the greenhouse effect (Osborne and Freyberg 1985) in order to plan curriculum and design instruction that builds on or challenges students' models (Driver et al. 1994).

The purpose of this study was to identify seventh grade students' mental models of the greenhouse effect, add to the extant literature base on students' geoscience and environmental science learning, and provide guidance to curricular development and instructional design. We also critique several science textbook diagrams in light of our findings. Specifically, the research question guiding this study was: What are seventh grade students' mental models of the greenhouse effect?

It may be argued that if earth and environmental science education is to improve citizens' understandings about global warming and climate change, students must develop mental models that are more closely aligned with scientific models. Students' mental model of the greenhouse effect grounds their understanding of global warming which guides their understanding of climate change. Thus, it is essential to grasp the constructs that students use to explain the greenhouse effect. A deeper understanding of students' mental models of the greenhouse effect would allow educators to identify potential impediments to learning (Ausubel, Novak, and Hanesian 1978). This provides insight toward planning curriculum and designing instruction that builds on students' existing mental models and current scientific understanding, encouraging curricular continuity and progression in learning (Driver et al. 1994).

Background

In brief, the greenhouse effect is a scientific phenomenon that involves complex processes. The key mechanism is that greenhouse gases in the atmosphere (troposphere) selectively absorb some of the sun's energy that is radiated by the Earth's surface and radiate this energy back toward Earth, warming the atmosphere. Greenhouse gases are any gases that absorb infrared radiation. Examples of the main greenhouse gases include water vapor, carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). This natural process regulates atmospheric temperature. The IPCC (2007) states that over the past century human activities, primarily the burning of fossil fuels, have enhanced the greenhouse effect by increasing the concentration of greenhouse gases in the atmosphere more than what would have occurred naturally. This increase in greenhouse gases has caused the atmosphere's overall temperature to increase, causing global warming.

Significance of study

In this section we provide a summary of the research on students' conceptions of the greenhouse effect, together with a general overview of the literature on mental and conceptual models. Although the research on students' conceptions reported below was conducted within schools, Rickinson (2001) notes that television serves as a major source of students' environmental information. Television provides students with access to information about global warming and climate change through nature programs, documentaries and movies. Thus, we acknowledge that students' conceptions of the greenhouse effect are likely to be influenced by television and other external sources as well as formal schooling. In fact, in our previous work (Shephardson et al. 2009) students indicated that the main source of their knowledge about the greenhouse effect came from:

- School science class/textbook (29%).
- TV and video programs (20%).
- Other individuals (not teachers) (6%).
- Other media source (6%).
- Greenhouse experience (5%).

Students' conceptions of the greenhouse effect

The research on students' conceptions of the greenhouse effect is rather sparse, with most studies using closed-ended response surveys. Furthermore, most studies have been conducted outside of the US, therefore, little is known about how US secondary school-age students conceptualize the greenhouse effect. For these reasons we reviewed 18 international studies that investigated secondary (Grades 6–12) students' conceptions of global warming and climate change.¹ We summarize the findings of these articles that pertain specifically to students' conceptions of the greenhouse effect.

Several studies have found that students do not necessarily have an explicit or accurate conception of the greenhouse effect (Andersson and Wallin 2000; Pruneau et al. 2001), or that students make a distinction between the greenhouse effect and global warming (Andersson and Wallin 2000; Koulaidis and Christidou 1999; Myers, Boyes, and Stanisstreet 2004; Boyes, Chuckran, and Stanisstreet 1993). Furthermore, some students erroneously link the greenhouse effect with stratospheric ozone depletion. For example, some students believe that the sun's rays are trapped by the ozone layer (Boyes and Stanisstreet 1997a; Koulaidis and Christidou 1999; Pruneau et al. 2003). Other students believe that the increased ultraviolet radiation, due to ozone depletion, results in global warming (Andersson and Wallin 2000; Boyes and Stanisstreet 1994, 1997a; Boyes, Stanisstreet, and Papantoniou 1999; Kilinc, Stanisstreet, and Boyes 2008; Koulaidis and Christidou 1999; Österlind 2005; Pruneau et al. 2003; Rye, Rubba, and Wiesenmayer 1997).

The students in these studies knew little about the greenhouse effect and were not able to identify greenhouse gases beyond carbon dioxide. For example, students did not consider water vapor as a greenhouse gas (Fisher 1998) and many have not even considered carbon dioxide as a greenhouse gas (Boyes et al. 1993; Boyes and Stanisstreet 1993; Boyes and Stanisstreet 1997a, b; Pruneau et al. 2001). For some students, air pollutants in general are greenhouse gases (Boyes and Stanisstreet 1997a; Koulaidis and Christidou 1999). Furthermore, some other students believe that carbon dioxide or greenhouse gases form a thin 'layer' or 'cover' in the Earth's atmosphere that traps the sun's rays or heat (Kilinc et al. 2008; Koulaidis and Christidou 1999; Pruneau et al. 2003), or that carbon dioxide or gases in general form a 'lid', 'skin' or 'roof' over the Earth (Andersson and Wallin 2000). Lastly, for the most part, these students did not make any distinctions between different kinds of solar energy (Boyes and Stanisstreet 1997, 1998; Fisher 1998; Koulaidis and Christidou 1999; Österlind 2005). Therefore, many students only see solar rays from the sun as involved in the greenhouse effect; they may lack the concept of terrestrial radiation (Koulaidis and Christidou 1999) and fail to understand the Earth's energy balance as a whole.

Mental and conceptual models

According to Greca and Moreira (2000, 2001), in order to understand the world, students construct internal representations or mental models that are based on their

existing knowledge and past experiences. These mental models are useful or functional in that they allow students to make predictions or explain phenomena or events. Greca and Moreira (2000, 2001) also argue that students are constantly revising their mental models based on new knowledge, ideas, concepts and experiences; and that students' mental models are personal, idiosyncratic and often unstable. Furthermore, language plays a role in the building of mental models; students build mental models based on what they already know about the meaning of words.

diSessa (1993), however, views students' explanations of phenomena to be spontaneous constructions based on elements of their existing knowledge structures or what he calls phenomenological primitives (p-prims). These p-prims are unconsciously used by students to make meaning of phenomena, situations, or events (diSessa 1993). Thus in different contexts, students may use different p-prims to make meaning, to explain phenomena, events or situations. In this sense, p-prims are not mental models, but are isolated knowledge structures that students use to make sense of the world.

Scientific or conceptual models, unlike mental models, are precise, complete and simplified representations of phenomena, situations or events based on scientifically accepted knowledge; they are external representations shared by a community of practitioners. Conceptual models may be too simplistic or too complex for practical application or use (American Association for the Advancement of Science 1990), which is why it is important to acknowledge students' mental models as equally valid, but alternative models of science phenomena.

Because students come to science classrooms with different cultural, educational, and personal experiences they each have different mental models (Glynn and Duit 1995). A key part of learning science is to facilitate students reflecting on their existing mental models and to build conceptual models (Glynn and Duit 1995; Greca and Moreira 2000; Libarkin, Beilfuss, and Kurdziel 2003) by modifying or restructuring existing cognitive structures (Mintzes, Wandersee, and Novak 1998). This model building process is dependent on the students' existing mental model (Greca and Moreira 2001; Libarkin et al. 2003). Well developed and organized mental models allow students to place new knowledge into existing models while poorly developed mental models may be easily modified based on new experiences (Libarkin et al. 2003). Thus, identifying students' mental models allows curriculum and instruction to be planned in a way that challenges students' mental models and/or that further develops students' mental models.

Theoretical and methodological perspective

We adopted a constructivist perspective for this study. Our objective was to understand the meanings constructed by students participating in a context-specific activity using language (Schwandt 1994), with a particular focus on the written language and drawings used by the students to represent and communicate their meaning (Holstein and Gubrium 1994; Kress et al. 2001). The signs and symbols represent the students' interests and motivation for making the sign or symbol at that point in time; they reflect what the student views as crucial and salient (Kress et al. 2001). Students generate the meaning for words, in part, based on their prior experiences and existing concepts (Schollum and Osborne 1987). These word meanings are constructed by students based on an interaction between scientific and everyday concepts. Scientific concepts influence everyday concepts, and everyday concepts influence scientific

concepts; this interaction shapes the conceptual system students make, represent and communicate (Vygotsky 1991). The underlying meanings in students' conceptions are contextualized because they represent students' cognitive constructions at a particular point in time (Patton 2002); and they reflect the unique social, educational, and cultural experiences of the students.

We interpreted the drawings and writings made by the students to represent their conceptions of the greenhouse effect – that is, we created constructions about the students' constructions. Thus, meaning is not discovered in the students' written language and drawings, but constructed in the mind of the authors within a socio-cultural context. The codes and categories are shaped and colored by our experiences and conceptions that are grounded in both environmental education and the geosciences (Patton 2002). Our interpretations of the students' responses, then, are just that, interpretations grounded in our experiences, conceptions, and perspectives about the greenhouse effect, global warming and climate change.

Qualitative data (i.e., student written and drawn responses) were collected via a survey of students (Driver et al. 1996). These were then analyzed for their content in an inductive manner to identify concepts and patterns in student responses. Inductive analysis as a qualitative methodology involves immersion into the details and specifics of the data in order to identify important categories and dimensions, as opposed to imposing preexisting expectations on the data (Patton 2002). The benefit of a survey was that it allowed us to collect data from many students with varying degrees of experience, including that of school science, providing us access to a breadth of student conceptions with varying degrees of sophistication than a smaller-scale study, e.g., a focus group (Driver et al. 1996). The survey permitted the characterization of students' conceptions and allowed us to identify trends or patterns in and across students' conceptions. At the same time, it enabled us to compare our findings to those of other researchers. Identifying the factors that contributed to the development of students' mental models of the greenhouse effect though, is beyond the scope of this study.

Method

Sample and data collection

We employed a purposeful sampling strategy (Patton 2002), using the seventh grade classrooms of three schools (D, M, T) with teachers involved in a climate change instructional development project² we coordinated. Seventh grade students are usually 12–13-years-old, in the first year of junior high school or its equivalent. Because we were interested in identifying students' mental models, we aggregated all of the student responses from the greenhouse effect task for a total sample of 225. As noted above, this provided a larger sample size and gave us the advantage of sampling a wide range of student responses so as to document the similarity, diversity and/or variation in their conceptions of the greenhouse effect (Driver et al. 1996; Patton 2002).

The sample included a range in student academic ability, from special needs students to high ability students, with about 55% of the students passing the state science achievement test (which is similar to the state level passing rate of 54%). The sample was primarily Caucasian (about 95%) with boys accounting for roughly 54% of the sample and girls 46%. We did not track responses by gender or ability. About 30% of the students were on a reduced or free lunch program. The schools were situated in small, rural communities in the midwest, US.

The greenhouse effect task

The greenhouse effect task was a draw-and-write activity designed to elicit students' ideas (Osborne and Freyberg 1985) and based on the draw and explain protocol (White and Gunstone 1992). The task used a written prompt to elicit student responses: 'Draw your understanding of the greenhouse effect; you can also use words to label parts of your drawing. In the space below your drawing, explain your drawing and explain how you know this'. A number of researchers have used similar tasks to elicit students' concepts about environmental and geoscience phenomena (see Alerby 2000; Anderson and Moss 1993; Barraza 1999; Bonnett and Williams 1998; Payne 1998; Simmons 1994). The students' written words and drawings are an active, deliberate meaning-making process and are conceptual visualizations or representations of their understandings that contain a number of individual concepts (Alerby 2000; Kress et al. 2001). The students' drawings, then, are representations of their mental models (Glynn and Duit 1995) and 'reveal qualities of understandings that are hidden from other procedures' (White and Gunstone 1992, 99). Thus, students' conceptions may be constructed from their graphic representations (Vosniadou and Brewer 1992). The written portion allows students to explain the drawings in their own words, and clarifies their conceptions for the authors. These written responses also allow the authors to validate meanings constructed from students' drawings.

Data analysis

Data analysis involved a content analysis of student responses resulting in the identification of student concepts. This process was inductive in nature; that is, instead of searching for pre-determined patterns, themes were allowed to emerge from the data as we constructed meaning from student responses (Patton 2002). The process followed that described by Rubin and Rubin (1995). From the first reading, core concepts (codes) were identified. These initial codes were revised after a second reading. The codes with common/overlapping themes were grouped into categories that reflected the students' conceptions. From these we constructed a category matrix that linked each code to a category (Erickson 1986) and that reflected the final categories of student conceptions. This enabled us to organize and check the data for saturation of categories and to eliminate redundant categories (Erickson 1986; Lincoln and Guba 1985). The categories were grouped into typologies that reflected the students' mental models. This process provided a degree of triangulation, reducing the influence of bias and subjectivity and increasing the validity of our analysis and interpretation of the results (Patton 2002; Strauss 1987). To ensure consistency in coding, an inter-rater reliability coefficient was calculated by comparing two of the authors' coding of 41 randomly selected tasks. The inter-rater reliability coefficient was 0.88. Coding was monitored throughout to ensure consistency and reliability.

Results

From the inductive analysis we identified 22 codes that we grouped into five categories that reflected the students' mental models of the greenhouse effect (Table 1). The five categories were: greenhouse gases (four codes), heating mechanism (nine codes), sources of greenhouse gases (three codes), ozone depletion/formation (two codes) and a greenhouse (four codes). The numbering of the mental models is presented as a means for distinguishing the different ways that students make sense of the greenhouse

Table 1. Student mental models of the greenhouse effect.

Greenhouse effect model	Totals (n = 225)
Model 5. Sun's rays are 'bounced' or reflected back and forth between the Earth's surface and greenhouse gases, heating the Earth (may or may not identify specific greenhouse gases)	30 (13%)
Model 4. Greenhouse gases 'trap' the sun's rays, heating the Earth (may or may not identify specific greenhouse gases)	78 (35%)
Model 3. Greenhouse gases, but no heating mechanism; simply gases in the atmosphere	38 (17%)
Model 2. Greenhouse gases cause ozone depletion or formation, which either allows more of the sun's rays to reach the Earth or causes the sun's rays to be 'trapped' or 'bounced' back toward Earth	14 (6%)
Model 1. 'Greenhouse' for growing plants	65 (29%)

effect and are not intended to imply a developmental sequence or value judgment. For each student response example we present the teacher-grade-student number in parentheses. All percentages are based on the total sample (n = 225).

We describe each of the models in detail below, noting that several elements cut across students' mental models (Table 2). For example, 16% of all students explicitly described carbon dioxide as a greenhouse gas. The ability to identify carbon dioxide as a greenhouse gas was most prevalent with Models 4 and 5, but also found with Models 2 and 3. Only students (3%) in the Model 5 category identified other greenhouse gases, such as methane and water vapor. Also, students (44%) in the Models 4 and 5 category tended to describe greenhouse gases or carbon dioxide as existing as a layer in the Earth's atmosphere, while in Model 2, they tended to identify an ozone layer. In general, students in the Model 3 category tended to describe air pollution as a greenhouse gas (10%) and were more likely to identify fossil fuels as a source of greenhouse gases (8%). Finally, students in the Model 2 and 5 categories identified the process of the sun's rays reflecting from the Earth's surface before being bounced back toward the Earth by the ozone layer (2) or greenhouse gases (5).

Table 2. Core concepts or elements of Mental Models 2, 3, 4, and 5.

Concept/element	Model 5 (n = 30)	Model 4 (n = 78)	Model 3 (n = 38)	Model 2 (n = 14)
Carbon dioxide/greenhouse gas	30 (13%)	78 (35%)	38 (17%)	14 (6%)
Other greenhouse gases: methane, water vapor	7 (3%)			
Sun's rays or heat	30 (13%)	78 (35%)		14 (6%)
Greenhouse gas/carbon dioxide layer	30 (13%)	69 (31%)		
Energy reflected 'bounced' from Earth surface	30 (13%)			7 (3%)
Energy reflected 'bounced' back by greenhouse gases/carbon dioxide	30 (13%)			
Sun's energy 'trapped' by greenhouse gases		78 (35%)		
Air pollutants as greenhouse gases			23 (10%)	2 (1%)
Ozone layer reflects/traps sun's energy				14 (6%)
Fossil fuels as source of greenhouse gas			18 (8%)	2 (1%)

Note: Percentages are based on the total sample, n = 225.

It should also be noted that no students explained in detail why a gas, such as carbon dioxide, was considered to be a greenhouse gas. That is, students did not explain why some gases absorb the sun's energy and why other gases do not. Also, regardless of the mental model, students explained that all of the sun's energy that strikes the Earth is retained within the Earth's atmosphere, that is, none of the energy escapes to space. Although a few students (<3%) did explain that some of the incoming 'sun's rays' or solar radiation is reflected by the Earth's atmosphere or clouds, most students did not incorporate clouds or aerosols in their responses elicited by the task. In essence they portrayed that all of the sun's rays incident on the Earth reach the Earth's surface. Thus these students do not conceptualize the greenhouse effect as a process within the Earth's energy or radiation balance.

Description of Model 5: sun's rays are 'bounced' or reflected back and forth between the Earth's surface and greenhouse gases, heating the Earth

Students (13%) who we categorize as holding Mental Model 5 explained the greenhouse effect as the reflection of the sun's energy by the Earth and by the greenhouse gases. Students who held this model may or may not identify specific greenhouse gases such as carbon dioxide. Thus, greenhouse gases are the 'gases' that cause the greenhouse effect. They explained that the 'sun's rays' or energy passes through the atmosphere and greenhouse gases and is 'bounced' or 'reflected' by the Earth and then 'bounced' or reflected back toward Earth by the greenhouse gases, preventing the sun's energy from escaping the Earth's atmosphere, warming the Earth (Figure 1). For example: 'The sun rays come down to Earth, bounce off, try to escape the atmosphere, but are bounced back to Earth, heating the Earth' (M-7th-2).³

Only two students who held Model 5 explained that the Earth's atmosphere and clouds reflect some of the sun's energy back toward space (Figure 1): 'Some of the sun's rays are bounced back to the sun' (T-7th-23).

For the rest of the students the Earth retains all of the sun's energy; the sun's energy is unable to escape the Earth's atmosphere because the greenhouse gases act as an 'insulator' or form a 'layer' that 'bounces' or reflects the sun's energy or heat back toward the Earth, heating the Earth (Figure 1): 'Keeps the heat in as an insulator, sun rays try to escape the atmosphere but are bounced back to Earth' (M-7th-1).

As illustrated in the student drawings and quotations (Figure 1), these students explained that the sun's energy or 'rays' are 'bounced' or 'reflected' by the Earth. There is no conception that the sun's rays are absorbed and radiated by the Earth or that the terrestrial radiation is absorbed by the greenhouse gases and radiated, warming the atmosphere. The model is built upon the concepts of bouncing and reflecting the sun's rays or energy. Only two students explained that some of the sun's energy escapes the Earth's atmosphere, 'keeping the earth's heat balance' (M-7th-10). Furthermore, most students explained the greenhouse effect in terms of the 'sun's rays' or 'heat from the sun' versus differentiating the radiative energy involved. For these students, the heating mechanism or radiative forcing is caused by a 'greenhouse gas layer' or 'carbon dioxide layer' in the atmosphere. This layer 'bounces' or 'reflects' the sun's energy or 'heat' back toward the Earth, warming the Earth. Thus, in addition to the 'bouncing' concept, students built their mental model on the 'layer' concept. The greenhouse gases are not viewed as being uniformly distributed in the atmosphere, but existing as a layer in the atmosphere.

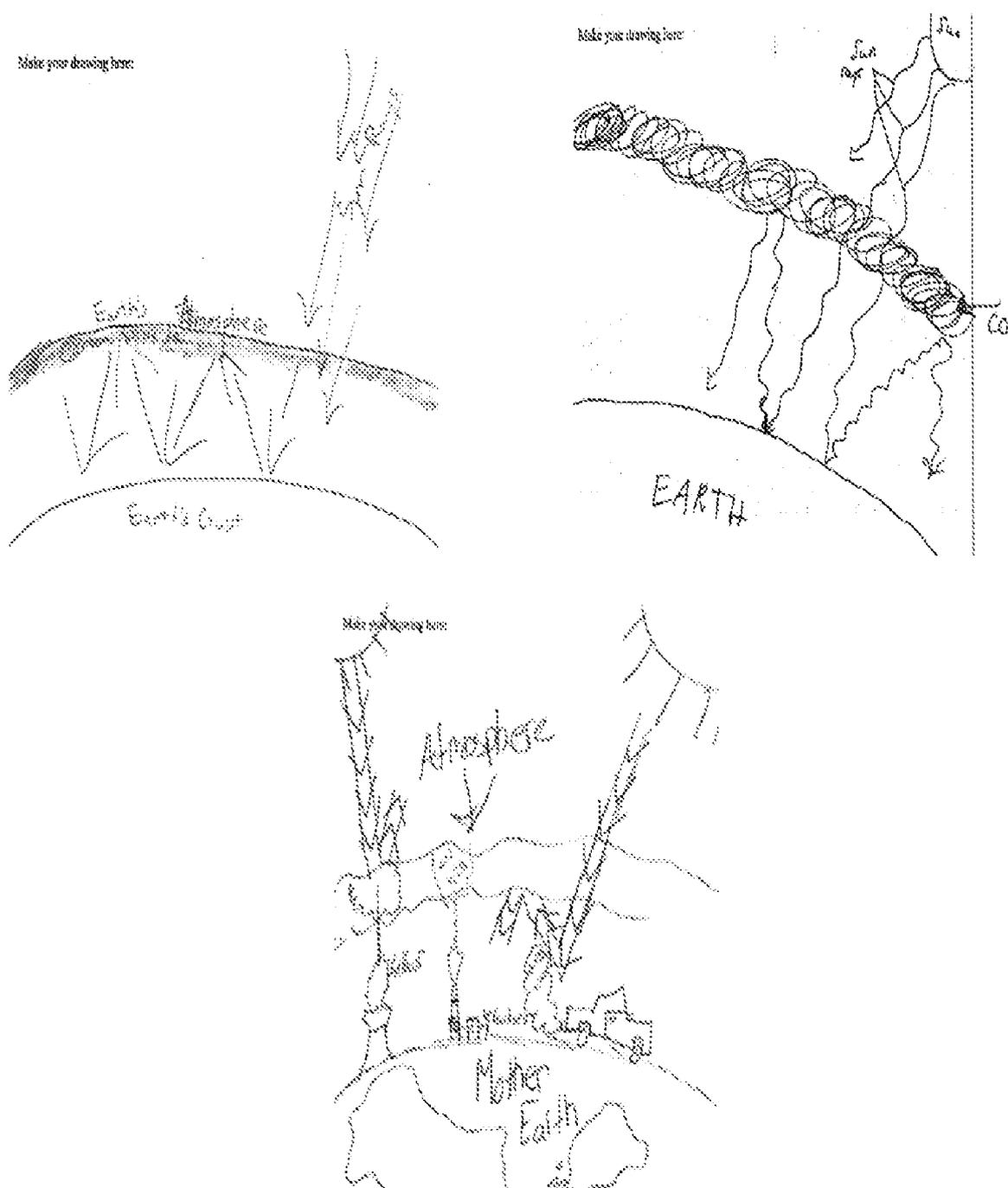


Figure 1. Example of student drawings representing that the sun's energy is reflected by the Earth and by atmospheric carbon dioxide/greenhouse gases.

Drawing 1 (top left). Sun rays come down into the earth's atmosphere and can't escape because of the CO₂ build up. They are bounced back to the Earth (M-7th-8).

Drawing 2 (top right). The sun releases rays which head toward Earth. When they reflected off the crust, the layer of CO₂ in our atmosphere reflect them blocking them from escaping (T-7th-12).

Drawing 3 (bottom). Some sun rays are bounced back by atmosphere. Gases like carbon dioxide and sulfur coming from factories and cars make a layer in atmosphere and cause the sun rays to bounce back and heat Mother Earth (D-7th-29).

Description of Model 4: greenhouse gases 'trap' the sun's rays, heating the Earth

The major difference between students who held Model 4 and Model 5 is the heating mechanism. Students (35%) who held Model 4, like Model 5, identified greenhouse

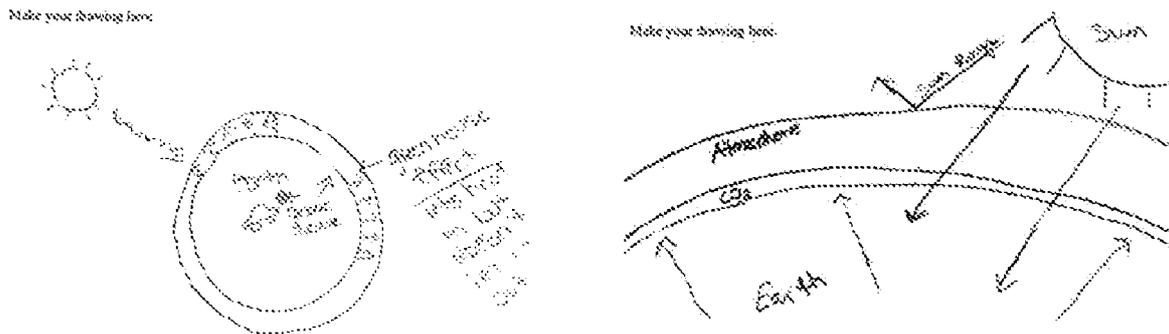


Figure 2. Example of student drawings representing that the sun's energy or heat is 'trapped' by the greenhouse effect.

Drawing 1 (left). The greenhouse effect is where there is a layer type thing and it lets heat in but traps carbon dioxide and heat and doesn't let it back into the atmosphere (D-7th-34).

Drawing 2 (right). Some sun rays bounce off atmosphere and some sun rays hit the Earth. The CO₂ levels in the atmosphere are high enough to let rays in, but not out (M-7th-2).

gases or carbon dioxide as atmospheric gases that cause the greenhouse effect. But, unlike Model 5, Model 4 students explained that the 'sun's rays', 'heat' or energy is 'trapped' in the atmosphere (Figure 2). The sun's rays are 'trapped' by the greenhouse or carbon dioxide layer or gases in the atmosphere, preventing them from escaping the Earth. They did not explain that the sun's energy is 'bounced' or 'reflected' by the Earth or by the greenhouse gases or carbon dioxide, the sun's energy is simply 'trapped' by greenhouse gases or carbon dioxide. The greenhouse gas layer functions as a barrier that prevents heat from escaping the Earth's atmosphere. Only two students who held Model 4 explained that not all of the 'sun rays' reach the Earth (Figure 2).

Description of Model 3: greenhouse gases, but no heating mechanism; simply gases in the atmosphere

Students (17%) who held Model 3 were aware of greenhouse gases but not the greenhouse effect; they did not explain a heating mechanism or the radiative forcing involved in the greenhouse effect (Figure 3). Students simply identified gases in the atmosphere. A small number of students (8%) identified fossil fuels (e.g., cars and factories) as the source of the greenhouse gases or carbon dioxide. Many of these students identified air pollution in general as the source of greenhouse gases and some identified carbon dioxide as a greenhouse gas. In essence, students who held Model 3 emphasized the source or type of greenhouse gas. Rather than the greenhouse effect, they focused on air pollution emitted by human activity.

Description of Model 2: greenhouse gases cause ozone depletion or formation, which either allows more of the sun's rays to reach the Earth or causes the sun's rays to be 'trapped' or 'bounced' back toward Earth

Students (6%) who held Model 2 commingled concepts of the greenhouse effect with ozone depletion or the ozone hole and the ozone layer. Students with this mental model believed that ozone depletion or the ozone hole causes the Earth to warm because more of the sun's energy reaches the Earth or that the ozone layer prevents

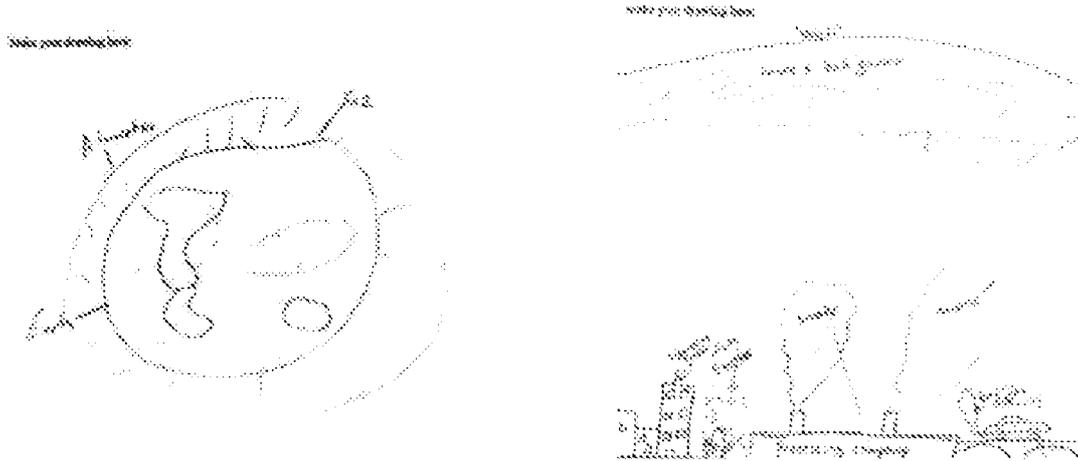


Figure 3. Example of student drawings representing greenhouse gases. Drawing 1 (left). The greenhouse effect is when CO₂ in the atmosphere covers the Earth (T-7th-24). Drawing 2 (right). Greenhouse effect is where a bunch of gasses and smoke are held in the Earth's atmosphere (D-7th-31).

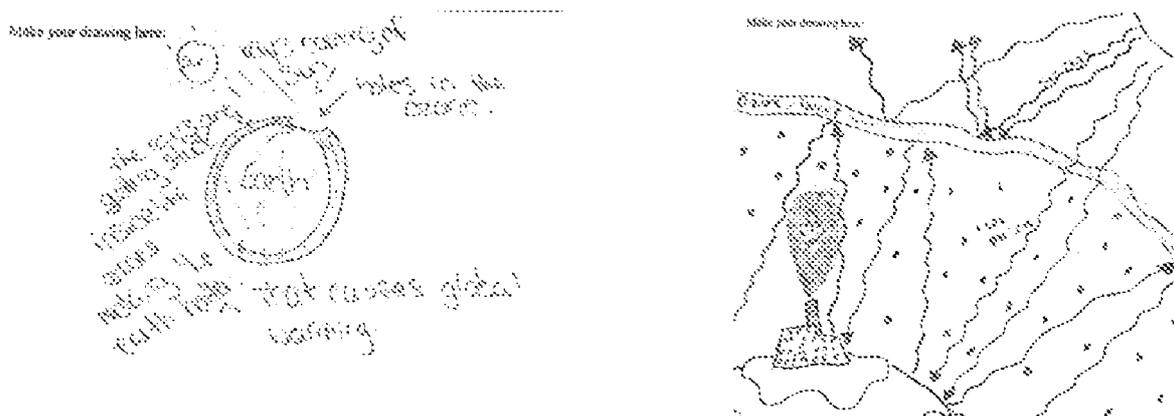


Figure 4. Example of student drawings representing ozone depletion or layer as the greenhouse effect. Drawing 1 (left). The carbon and pollution that we make tear up the ozone layer and have created a hole in them. The sun rays get stuck in the ozone and make the earth hotter causing global warming (D-7th-16). Drawing 2 (right). CO₂ and sun rays cause green house gases which form ozone and ozone keeps sun rays in making earth hotter (D-7th-2).

the sun's rays from escaping (Figure 4). In fact, the greenhouse gases (e.g., carbon dioxide) either 'tear up' the ozone layer causing the ozone hole or result in the formation of the ozone layer which prevents the sun's rays from escaping (Figure 4). These students' mental model was similar to students who held Models 4 and 5 in that the sun's energy is 'trapped' or 'stuck' (Model 4) or is 'bounced' or reflected (Model 5) by the ozone layer. These students also build their mental model using the 'layer' concept, albeit a layer of ozone.

Description of Model 1: 'greenhouse' for growing plants

Students (29%) who explained the greenhouse effect as a 'greenhouse' were categorized as holding Model 1 (Figure 5). These students created a literal representation of

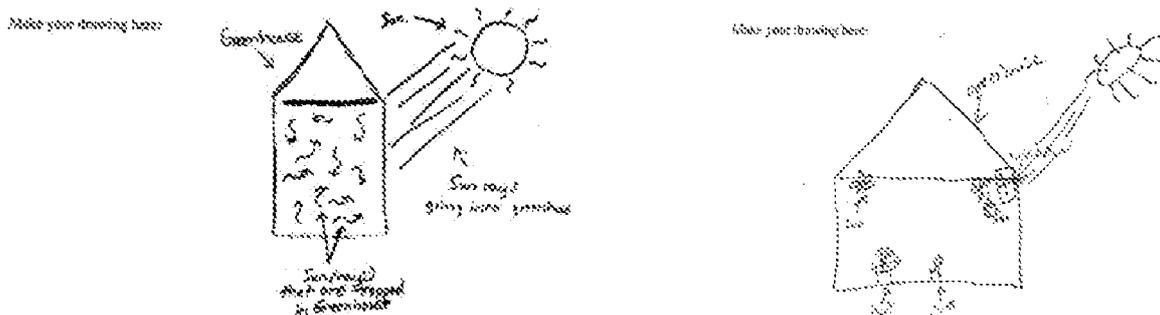


Figure 5. Example of student drawings representing the greenhouse effect as a 'greenhouse'. Drawing 1. Sun rays go through glass and are trapped in greenhouse heating the air inside (M-7th-10).

Drawing 2. It's a greenhouse with plants inside the house with fans and the sun coming through the windows for the plants (D-7th-23).

the word 'greenhouse'. These students likely do not understand the greenhouse effect, thus they represent the concept based on their everyday experience with and knowledge about a 'greenhouse'. They connect the word 'greenhouse' to a concrete object they are familiar with; their meaning is shaped by the everyday concept of 'greenhouse'. Thus, everyday language guided these students' meaning-making (Duit 1991) and how they represented their mental model of the greenhouse effect.

Discussion

It is important to stress that the mental models of the greenhouse effect described in this article reflect the sample as a whole and that an individual student, under a different context, might convey a different mental model. The categories are an attempt to characterize the different mental models students hold about the greenhouse effect and to summarize these in such a way as to inform practice and to further our understanding about how students make meaning of the natural world.

The students' mental models of the greenhouse effect contain similar concepts found in previous findings. For example, some of these students indicated that air pollutants in general are greenhouse gases (see Boyes and Stanisstreet 1997a; Koulaidis and Christidou 1999) and that carbon dioxide or greenhouse gases form a layer in the atmosphere that traps the sun's energy (see Andersson and Wallin 2000; Kilinc et al. 2008; Koulaidis and Christidou 1999; Pruneau et al. 2003). Similarly, few students made a distinction between types of solar energy, with most referring only to 'solar rays' or 'sunrays' (see Boyes and Stanisstreet 1997, 1998; Fisher 1998; Koulaidis and Christidou 1999; Österlind 2005). Like Koulaidis and Christidou (1999) most students did not specifically identify terrestrial radiation, but simply that the sun's rays are 'bounced' back by the Earth. Although students in many studies (Andersson and Wallin 2000; Boyes and Stanisstreet 1994, 1997a; Boyes, Stanisstreet, and Papantoniou 1999; Kilinc, Stanisstreet, and Boyes 2008; Koulaidis and Christidou 1999; Österlind 2005; Pruneau et al. 2003; Rye, Rubba, and Wiesenmayer 1997) confuse the ozone layer or ozone depletion with the greenhouse effect, only a small number of students from this study explained the greenhouse effect in terms of stratospheric ozone.

Based on the mental models identified it is apparent that these students lacked a clear understanding of the greenhouse effect. At best 48% of the students realized that greenhouse gases, whatever they may be, cause the greenhouse effect and that the

sun's energy is either 'trapped' by or 'bounced' back to the Earth by the greenhouse gas layer. On the other end of the spectrum, 29% of the students lacked an understanding of the greenhouse effect. On the bright side, students who hold Mental Models 3, 4 and 5 and probably students who hold Mental Model 2 have fairly well developed mental models that are likely to be easily modified with the appropriate curriculum and instructional experiences.

Because most students' mental model lacked a concept of solar energy, a distinction needs to be made between ultraviolet radiation, visible light, infrared radiation and other forms of solar energy; that is, sunlight as a spectrum of different bands of radiation. It is also essential to address the notion that different greenhouse gases and atmospheric gases absorb electromagnetic radiation at different wavelengths, explaining why some gases absorb the sun's energy (e.g., water vapor and carbon dioxide) and others do not (e.g., nitrogen and oxygen). At the same time, none of the students' mental models dealt specifically with the Earth's absorption and radiation of the sun's energy, i.e. the notion of terrestrial radiation. The role of clouds and aerosols or particles in reflecting or absorbing solar radiation was also lacking in the students' mental models. Addressing these concepts will likely foster the development of students' mental models of the greenhouse effect as part of the Earth's energy budget or balance. The narrow emphasis on anthropogenic sources of greenhouse gases suggest that students also need to be exposed to other human, as well as natural, modifiers of greenhouse gases such as animal waste, landfills, forest fires and land cover and land use changes.

Planning curriculum and designing instruction is a difficult and challenging process made even more taxing by the necessity to start from students' mental models, considering that the progression in students' mental models is not a linear process. Based on the results of this study and previous findings it would appear that a curriculum built from students' mental models would need to address the following concepts, which link to the National Research Council (NRC) 5–8 science education standards (Table 3):

- Carbon cycle, fossil fuels (energy) and greenhouse gases.
- Other human and natural sources of greenhouse gases (e.g., forest fires, animal waste, landfills, land use).
- Greenhouse gases (e.g., water vapor, carbon dioxide, methane, nitrous oxide).
- Uniform distribution of greenhouse and atmospheric gases.
- Absorption and radiation of energy—energy transfer.
- Greenhouse effect, radiative forcing (infrared radiation) and the Earth's energy balance.
- Distinction between types of solar radiation and solar and terrestrial radiation.
- Greenhouse gases and ozone depletion.
- The greenhouse effect and global warming.
- Natural versus human sources of greenhouse gases and personal solutions and actions.

Many of the students' mental models of the greenhouse effect are re-enforced or even built on the concepts displayed in the diagrams found in most earth and environmental science textbooks. For example, the greenhouse effect represented in Lapinski, Schoch, and Tweed (2003, 366) implies the existence of a 'greenhouse gas layer' above the Earth's surface that traps and reflects the sun's energy. In the textbook representation of the greenhouse effect in Sager et al. (2002, 466) 'sunlight' is

Table 3. The National Research Council (NRC) 5–8 standards.

Standard	Standard excerpt
Physical science	Heat moves in predictable ways, flowing from warmer objects to cooler ones... The sun is a major source of energy for changes on the earth's surface... A tiny fraction of that light reaches the earth, transferring energy from the sun to the earth. The sun's energy arrives as light with a range of wavelengths, consisting of visible light, infrared, and ultraviolet radiation.
Earth and space science	The atmosphere is a mixture of nitrogen, oxygen, and trace gases that include water vapor... Living organisms have played many roles in the earth system, including affecting the composition of the atmosphere... The sun is the major source of energy for phenomena on the earth's surface, such as growth of plants, winds, ocean currents and the water cycle...
Science in personal and social perspectives	Human activities also can induce hazards through resource acquisition, urban growth, land-use decisions, and waste disposal. Such activities can accelerate many natural changes.

transformed into 'infrared rays' that are reflected by the atmosphere. At the same time, textbook representations represent factories discharging smoke (air pollutants) into the 'greenhouse gases' layer of the atmosphere. The plain interpretation is that, air pollution in general is a greenhouse gas and factories in particular are the major source of 'greenhouse' gases. Thus, the greenhouse effect is conveyed as an anthropogenic phenomenon and not a natural process. The impression that science textbook diagrams can have on students may be seen in the students' drawings where the greenhouse effect drawn is very similar to the textbook diagrams.

When designing instruction, science educators need to take care not to reinforce student conceptions that the greenhouse effect 'traps' all of the sun's energy and that carbon dioxide is the only greenhouse gas or that air pollution in general is a greenhouse gas. For example, the typical 'greenhouse' demonstration where vinegar and baking soda are mixed to produce carbon dioxide in a tank that is then covered and heated with a light source, is not an exact physical model of the Earth's greenhouse effect and must be cautiously presented to students, stressing the limitations of the physical model. Failure to address these limitations may reinforce limited mental models, especially those represented by Models 3 and 4, whereby the glass prevents heat loss or 'traps' all of the heat. Students need to realize that the elements of the physical model do not necessarily correspond to elements in reality (Greca and Moreira 2001). By addressing students' mental models of the greenhouse effect and designing curriculum and instruction that builds from students' mental models and that moves toward a scientific perspective, science educators develop the foundation from which an understanding of global warming and climate change may be anchored.

Notes

1. The studies are from the 1990s onwards, and largely with students in western, industrialized states, e.g., European countries, Canada, Australia, etc.

2. The work reported in this manuscript was supported by the National Science Foundation (NSF), award number Geo 0606922. It is also described in Shephardson et al. (2009).
3. The coding represents (school–grade–student number), as used in Shephardson et al. (2009).

Notes on contributors

Daniel P. Shepardson is professor of geoenvironmental and science education in the departments of curriculum and instruction and earth and atmospheric sciences at Purdue University.

Soyoung Choi is a graduate student in the department of curriculum and instruction at Purdue University.

Dev Niyogi is associate professor in the departments of agronomy and earth and atmospheric sciences at Purdue University. He is also the Indiana state climatologist.

Umarporn Charusombat is a graduate student in the department of earth and atmospheric sciences at Purdue University.

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