PART I: DEVELOPMENT OF A CONCEPT INVENTORY ADDRESSING STUDENTS' BELIEFS AND REASONING DIFFICULTIES REGARDING THE GREENHOUSE EFFECT; PART II: DISTRIBUTION OF CHLORINE MEASURED BY THE MARS ODYSSEY GAMMA RAY SPECTROMETER

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As members of the Dissertation Committee, we certify that we have read the dissertation prepared by John Michael Keller
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DEDICATION

To Sophie, Sean, Liam, Andrew, Caitlin,
and all young people of our planet:

May we provide learning environments
allowing you to construct accurate knowledge
to thoughtfully address planetary challenges.

To Josh, Lauren, Jodi, Lauren,
and others whose lifework had only just begun:

You've touched our lives through your love.

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ABSTRACT

This work presents two research efforts, one involving planetary science education research and a second involving the surface composition of Mars. In the former, student beliefs and reasoning difficulties associated with the greenhouse effect were elicited through student interviews and written survey responses from >900 US undergraduate non-science majors. This guided the development of the Greenhouse Effect Concept Inventory (GECI), an educational research tool designed to assess pre- and post-instruction conceptual understanding of the greenhouse effect. Three versions of this multiple-choice instrument were administered to >2,500 undergraduates as part of the development and validation process. In contrast to previous research efforts regarding causes, consequences, and solutions to the enhanced greenhouse effect, the GECI focuses primarily on the physics of energy flow through Earth's atmosphere. The GECI is offered to the science education community as a research tool for assessing instructional strategies on this topic.

It was confirmed that the study population subscribes to several previously identified beliefs. These include correct understandings that carbon dioxide is an important greenhouse gas and the greenhouse effect increases planetary surface temperatures. Students also commonly associate the greenhouse effect with increased penetration of sunlight into and trapping of solar energy in the atmosphere. Students intermix concepts associated with the greenhouse effect, global warming, and ozone depletion. Reinforcing the latter concept, a majority believe that the Sun radiates most of

its energy as ultraviolet light. Students also describe inaccurate and incomplete trapping models, which include permanent trapping, trapping through reflection, and trapping of gases and pollution. Another reasoning difficulty involves the idea that Earth's surface radiates energy primarily during the nighttime.

The second research effort describes the distribution of chlorine on Mars measured by the Mars Odyssey Gamma Ray Spectrometer (GRS). The distribution of chlorine is heterogeneous across the surface, with a concentration of high chlorine centered over the Medusa Fossae Formation. The distribution of chlorine correlates positively with hydrogen and negatively with silicon and thermal inertia. Four mechanisms (aeolian, volcanic, aqueous, and hydrothermal) are discussed as possible factors influencing the distribution of chlorine measured within the upper few tens of centimeters of the surface.

CHAPTER 1: INTRODUCTION

1.1 Overview

This work presents two different research projects: 1) research into student beliefs and reasoning difficulties associated with the greenhouse effect, and 2) investigation into the global distribution of and probable geologic mechanisms influencing chlorine at the near-surface of Mars as measured by the 2001 Mars Odyssey Gamma Ray Spectrometer (GRS). The first four chapters address the former pursuit and describe the development and testing of the Greenhouse Effect Concept Inventory (GECI). The GECI is a multiple-choice instrument designed to measure pre- and post-instruction understanding of the greenhouse effect using distracters based upon known student naïve beliefs and reasoning difficulties. A review of the literature revealed that while significant research has been conducted into student beliefs about the causes, consequences, and solutions to the enhanced greenhouse effect, few efforts have focused specifically on student models of the physical mechanisms for the natural greenhouse effect or looked at post-instructional gains. Through coding analyses of student-supplied written responses from six iteratively developed survey instruments administered to over 900 undergraduate students, common themes and trends in student beliefs and understanding were systematically identified. Student language from this analysis was used to create survey items on the GECI. As part of the development process, student interviews and student-written responses guided revisions and corroborated additional insights gained from analyses of each version of the GECI. Conventional education research metrics along with an expert review process were also used to validate the effectiveness and reliability of the final survey instrument, GECI.vC. Finally, the GECI was administered to groups of students receiving differing educational interventions (types of educational activities and experiences) on the topic of the greenhouse effect. The Greenhouse Effect Concept Inventory allows the opportunity to measure learning gains based upon differing educational interventions.

The final chapter of this dissertation addresses a second research project involving analysis of gamma ray data from Mars GRS. The global distribution of chlorine at the near-surface of the planet is described and possible geologic interpretations are discussed. Attention is focused on a region of high chlorine centered over the Medusae Fossae region to the west of the Tharsis volcanoes. Mechanisms involving aeolian, volcanic, aqueous, and hydrothermal processes are examined. This work has been accepted and will appear in a special issue of the Journal of Geophysical Research (JGR).

The diversity of these two projects reflects the unique research interests and professional goals of the author, who wanted to pursue a graduate program providing experiences robust and rich in science content, science research, and science education research. Both the Boynton Gamma Ray Spectrometer Group at the Lunar and Planetary Laboratory and the Conceptual Astronomy and Physics Education Research (CAPER) Team at Steward Observatory provided research environments to make this possible. Rather than pursuing either a traditional research project in planetary sciences or a traditional education research project, the author chose to round out his graduate experience by working on both. The data collection techniques and theoretical frameworks associated with these two research projects differ. One provides insight into student thinking through interviews, surveys, and classroom observations while the other uses a germanium crystal in orbit around Mars to collect gamma ray photons. At the same time, the two share common foundations and goals central to research. Both demand systematic approaches based upon observation and logical inference. Both involve analysis of data that is statistical in nature and represents only a sample of the population being studied remotely (atomic nuclei at the surface of Mars via gamma ray spectrometry versus the beliefs of undergraduates via surveys and interviews). Mars GRS has provided valuable elemental information about the near-surface of Mars. Equally important, addressing beliefs about the greenhouse effect will likely play an important future role in scientific, educational, and political arenas.

All further discussion of the gamma ray research project regarding chlorine on Mars is saved for Chapter 5. The remainder of Chapter 1 serves as an introduction to the education research project regarding student beliefs about the greenhouse effect. The chapter describes the basis and motivation for research into student misconceptions, a brief overview of current scientific thinking about the greenhouse effect, a review of previous related research efforts, and an outline of the goals of the education research project.

1.2 Basis and Motivation for Misconception Research

Education research into student misconceptions and reasoning difficulties is grounded in the modern educational theory of constructivism. Simply put, constructivist theory holds that students do not receive knowledge; rather students construct knowledge based upon pre-existing ideas and experiences (Vygotsky, 1978; Bodner, 1986; Mestre, 1991; Cobb, 1994). Every human possesses a mental framework of knowledge that he or she has actively created and built upon throughout life based upon personal interpretations of experiences and interactions with the world. Importantly, these personal beliefs and ideas are often naïve, incomplete, or inaccurate while at the same time strongly entrenched and resistant to change (Novak, 1988). This perspective holds that understanding is not something that can be simply inserted into minds through injection or infusion of information. Rather, students must actively engage and interact with information and experiences that challenge, confront, and conflict with their personal interpretations of reality if lasting learning and conceptual change are to occur. After misconceptions have been challenged, however, it is equally important that reasonable and more accurate explanations be provided for students to adopt and build upon.

The implication of constructivist theory for science education is that students come to the science classroom with a multitude of preconceptions and misconceptions about science topics (McDermott, 1984; McDermott and Redish, 1999). These beliefs often miss the mark of describing physical phenomena in conceptually and scientifically accurate and complete ways. Several thousand studies have attempted to ascertain commonly held misconceptions related to various science topics (Duit, 2006). Research into student misconceptions can help guide curricular choices, focus attention to key conceptual difficulties, and provide insight into the types of learning experiences and activities useful in addressing these misconceptions (McDermott, 1984; Driver et al., 1985; McDermott, 1991; Dove, 1998). This effort is particularly important because, as mentioned above, misconceptions are deeply embedded within student's personal conceptual frameworks and are resistant to conceptual change (Driver et al., 1985; Novak, 1988; Mestre, 1991).

Misconception research has also been used to quantify, validate, and expand aspects of Pedagogical Content Knowledge (PCK) that instructors develop through their own constructivist learning cycle (Shulman, 1986). Based upon this perspective, PCK is different from pedagogical knowledge which involves a set of methods and skills essential for motivating and coordinating effective instruction. It is also different from content knowledge which embodies assumptions, conceptual frameworks, and skills associated with a specific field or discipline. Rather, PCK is a third type of knowledge that instructors develop as they gain exposure to helping students confront and resolve science misconceptions. Content knowledge regarding the nature and mechanism of Rayleigh scattering is related to, but fundamentally different from, pedagogical content knowledge regarding effective techniques for helping a student understand why the sky is blue. Misconception research provides a useful tool for the development and understanding of PCK. For example, insights that students have difficulty acknowledging the existence of air (Stavy, 1990) highlights the importance of clarifying with students that the blue sky is actually made up of air molecules before introducing the concept of light scattering. Thus, misconception research can support the development and implementation of PCK in the classroom.

The misconception study described here involves student ideas and reasoning difficulties related to the greenhouse effect. Interestingly, the original inspiration for this project resulted from the development of an on-line distance learning class for secondary teachers regarding multi-wavelength astronomy created in 2001 (Keller and Slater, 2003a; 2003b). While contemplating ways to help students better understand the nature of airborne infrared astronomy, it was recognized that the greenhouse effect is a much more commonly discussed topic involving several of the same conceptual components. Both involve greenhouse gases which are largely opaque to infrared light. Astronomers cannot collect infrared photons from stars and galaxies from the surface of the Earth for the same reason that terrestrial infrared radiation has difficulty passing directly through the atmosphere back to space. The relevance of the greenhouse effect to the field of planetary science along with the richness of student beliefs on this topic and related physics concepts further supported this research pursuit. A number of the physics and earth science concepts relevant to the greenhouse effect are also topics central to the National Research Council's National Science Education Standards (NRC, 1996). Finally, understanding student reasoning difficulties is an important element of addressing public understanding and future political debate centered on the anthropogenic greenhouse effect, global warming, and global climate change.

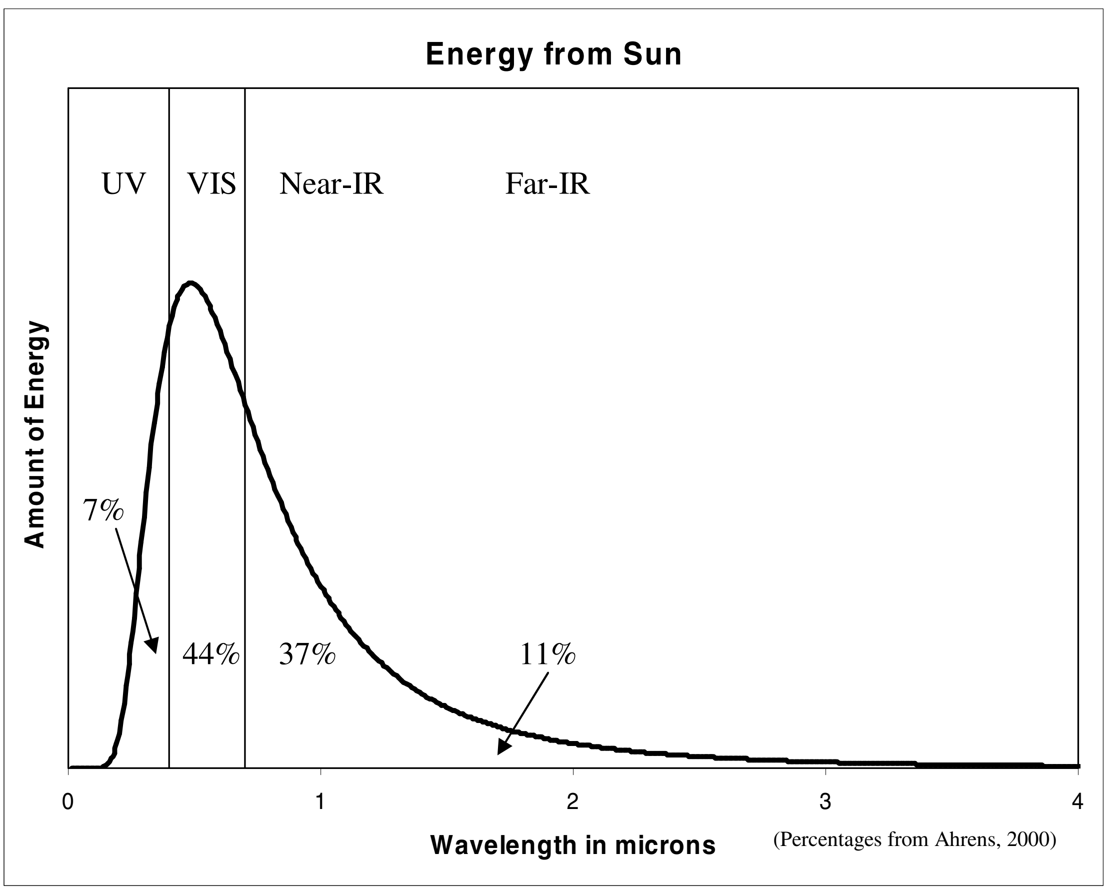
1.3 Scientific Context Regarding Greenhouse Effect

The concepts of both the greenhouse effect and enhancement of the greenhouse effect due to increased carbon dioxide levels resulting from the burning of fossil fuels were first described over a century ago by Arrhenius (1896). Provided below is a brief summary of current definitions and scientific understandings of the natural and anthropogenic greenhouse effect.

1.3.1 Atmospheric Greenhouse Effect

A thorough understanding of the flow of energy through Earth's atmosphere starts with a description of the types of energy radiated by the ultimate source of atmospheric heating, the Sun. Figure 1-1 reproduced from Ahrens (2000) shows the spectrum of the Sun along with a description of the percentage of energy given off in each of the labeled spectral regions.

Figure 1-1 Energy spectrum of the Sun



It is important to clarify that the peak of this spectrum occurs at visible energies and that over 90% of the Sun's energy is released at visible, near-infrared, and far-infrared wavelengths combined. As will be shown throughout Chapters 2-4, a widely held misconception among novices and even some experts is that the Sun radiates a large fraction of energy at ultraviolet energies. However, less than 10% of the energy given off by the Sun is actually in the form of ultraviolet energy.

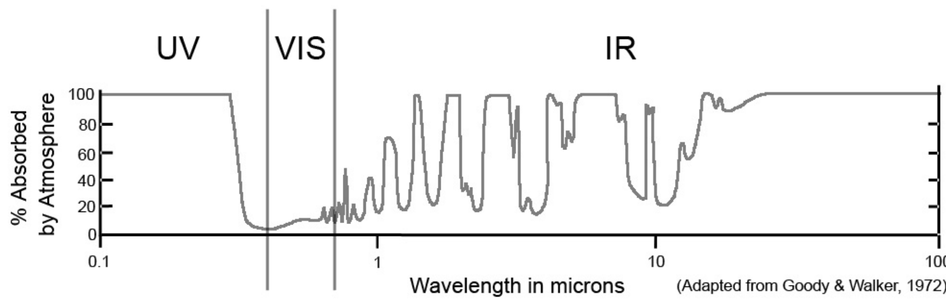
Energy from the Sun radiates into space and some of it is intercepted by planets in the solar system. Based upon the concept of energy equilibrium, the net amount of energy absorbed by a planet must equal the amount of energy leaving the planet. This allows us to establish the following relationship involving albedo (A), solar flux at the planet-Sun distance (F_s), the cross-sectional area of the planet (πa^2), the flux of radiation leaving the planet ($\varepsilon\sigma T_{eff}^4$), and the surface area of the planet ($4\pi a^2$).

$$(1-A)F_s \pi a^2 = 4\pi a^2 \varepsilon\sigma T_{eff}^{\ 4}$$

This equation can be solved for T_{eff}, the "effective temperature" or equilibrium temperature of the planet. Using values for Earth, with an albedo of 30%, a solar constant of 1367 W/m^2 (Hartmann, 1994), and emissivity ~1, the effective temperature of Earth is 255K. This value, which is also the emission temperature of the planet, has been confirmed through satellite measurements.

The fact that the average temperature at the surface of our planet is actually 288K, fully 33K warmer than the effective temperature, is due to the greenhouse effect and the fact that greenhouse gases in our atmosphere (primarily water vapor and carbon dioxide) interact with light in a wavelength dependent manner. Although largely transparent to visible energy, greenhouse gases absorb infrared energy at finite frequency bands associated with the rotational and vibrational energy modes of the molecule. This is seen in the diagram below taken from Goody and Walker (1972) which shows the percent of energy absorbed by the atmosphere as a function of wavelength.

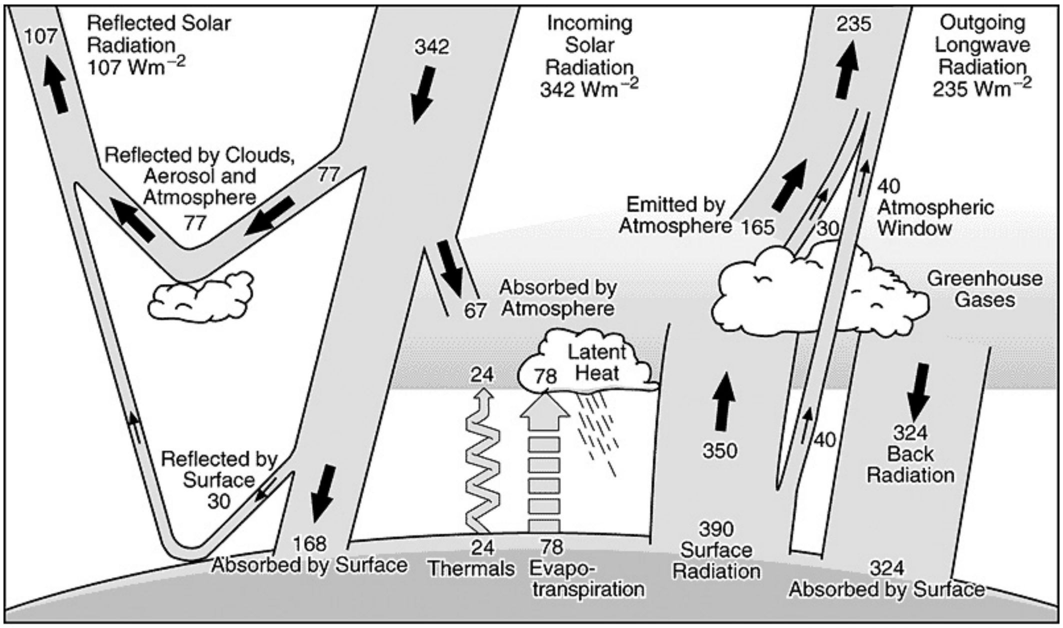
Figure 1-2 Percentage of energy absorbed by Earth's atmosphere



Thus, while visible light is able to pass into and out of the atmosphere with minimal interactions with greenhouse gases, infrared radiation is more frequently absorbed and re-emitted in random directions. Greenhouse gases essentially decrease the thermal conductivity of the atmosphere at infrared energies, which in turn affects its temperature profile.

Importantly, the infrared radiation re-emitted by greenhouse gases is given off in all directions, so infrared energy propagates both up towards space and down back towards the surface of the Earth. The latter results in a sizeable amount of "back radiation," which actually contributes more heating to the surface of the planet than does heating by direct solar radiation. In describing the global mean energy budget of the planet using satellite data, Kiehl and Trenberth (1997) determine that 342 W/m^2 of incoming solar radiation arrives at the top of the atmosphere. This is a quarter of the value used for F_s above because the solar radiation intercepting the Earth's cross-sectional area (πa^2) is evenly distributed across the surface area of the planet ($4\pi a^2$). Of this, 107 W/m^2 (31%) is reflected either by clouds, aerosols, the atmosphere, and the surface. The remaining 235 W/m^2 is absorbed by the atmosphere (67 W/m^2) and the surface (168 W/m^2). However, the surface also absorbs almost double this amount of energy (324 W/m^2) from back-radiation re-emitted by greenhouse gases as infrared energy. Thus, the total amount of heating at the surface is 492 W/m^2. Energy balance is maintained because an equal amount of energy is released from the surface as well (390 W/m^2 as terrestrial infrared radiation, and 102 W/m^2 through convection of thermals and evapo-transpiration of latent heat in the atmosphere). Ultimately, 235 W/m^2 of energy is radiated or transmitted by the atmosphere back to space. This energy released back to space along with the reflected energy described above perfectly balances the incoming solar energy. Thus, the surface, atmosphere, and top of the atmosphere remain in energy balance even though back-radiation from greenhouse gases enhances the total exchange of energy at the surface-atmosphere interface. The result of this enhancement is a corresponding increase in surface temperature. The flow of energy described above is shown in Fiugre 1-3 in a diagram from Kiehl and Trenberth (1997).

Figure 1-3 Energy flow diagram for Earth's atmosphere



(Source: Kiehl and Trenberth, 1997)

The above description encapsulates the fundamental aspects of complete and conceptually accurate understanding of the process of the greenhouse effect. To reinforce the concept here, a paragraph describing the greenhouse effect that was originally developed as part of a student intervention (see Chapter 4) is provided below:

> The flow of energy shown in Figure 3 [not shown] is the source of the natural "atmospheric greenhouse effect." Visible light penetrates the atmosphere and is absorbed by the surface. The heated surface gives off infrared light that is then absorbed by the atmosphere. The heated atmosphere gives off infrared light out to space and also back down to Earth's surface, making the surface temperature warmer than it would be without a greenhouse effect. The amount of energy entering and leaving the Earth system is balanced, but the Earth's surface temperature is warmer because the surface is heated both by visible light from the Sun and infrared light from the atmosphere.

1.3.2 Enhanced Greenhouse Effect

Currently, the two most important gases contributing to the greenhouse effect on Earth are water vapor and carbon dioxide. Other greenhouse gases present at lower concentration levels include methane, ozone, and nitrogen oxides. Burning of fossil fuels has increased the amount of carbon dioxide in the atmosphere by over 30% of the pre-industrial average of 280 ppm. There is also strong evidence that the average surface temperature of the planet has warmed between 0.4 to 0.8ºC in that same time-span of 150 years (IPCC, 2001). This increase in surface temperatures has been termed “global warming,” and there is strong consensus within the planetary and atmospheric science community that this warming has been influenced by an “enhanced greenhouse effect” resulting from increases in carbon dioxide levels. This has also been termed the “anthropogenic greenhouse effect,” the “human-enhanced greenhouse effect,” and the “human-induced greenhouse effect.” While other factors also affect global mean temperatures, the enhanced greenhouse effect appears to be an important “radiative forcing” that likely contributes to global warming.

1.4 Literature Review

1.4.1 Scope of the Literature Review

This section provides a review of the literature in science education research relevant to this investigation of student beliefs about the greenhouse effect. Before reviewing these works, however, it should first be noted that an impressive number of previous studies have investigated student misconceptions on a range of science topics. Indeed, a bibliography of over 7000 works compiled by Duit (2006) “attempts to document research on teaching and learning science with a certain emphasis on research from constructivist perspectives" and particular attention towards teachers' and students' conceptions. Annotated bibliographies have also been compiled regarding misconceptions in physics (McDermott and Redish, 1999), chemistry (Garnett et al., 1995; Özmen, 2004), astronomy (Bailey and Slater, 2005), and earth science (Philips, 1991; Henriques, 2002).

Included in these studies are research efforts regarding general physics principles that are fundamental to student understanding of the greenhouse effect. In a seminal papers on student beliefs about the greenhouse effect, Boyes and Stanisstreet (1993) recommend that further research must be carried out regarding the manner in which children synthesize "the concepts of energy, heat, radiation, absorption, equilibrium, and photosynthesis, and others when thinking about global warming." Relevant to this pursuit are previous studies regarding the concept of energy (Solomon, 1986), the nature and interactions of light (Stead and Osborne, 1980; Guesne, 1985), thermal energy and heat, (Erickson, 1979; Erickson, 1980; Erickson and Watts, 1985; Arons, 1999), gases, atmospheres, and weather (Nussbaum, 1985; Sere, 1985; Stavy, 1990; Dove, 1998; Spiropoulou et al., 1999; Henriques, 2002), and photosynthesis (Stavy et al., 1987). A thorough review of each of these topics is beyond the scope of this literature review. However, guiding principles from these works (e.g., student difficulties distinguishing between reflection and radiation of light, common misconceptions of heat as a substance rather than a transfer of thermal energy) have been considered during the analysis of student interviews and the development of survey items on the GECI.

Within the scope of this literature review, several previous studies have focused specifically on misconceptions regarding the greenhouse effect and ozone depletion. Before discussing findings, however, it is important to clarify that many of these research efforts address student beliefs about the causes, consequences, and solutions related to the "enhanced greenhouse effect" rather than specifically addressing the physics of the "natural greenhouse effect."

1.4.2 Previous Research Efforts

Focused attempts to characterize public understanding of the enhanced greenhouse effect appear in the literature in the early 1990's. These include a survey of 321 attendees at a public-awareness conference held in 1988 on the enhanced greenhouse effect in Australia (Henderson-Sellers, 1990) and another study involving ethnographic interviews with a small sample of 14 American adults (ages 31-81) "from diverse walks of life" (Kempton, 1991). The first concerted effort to elicit understanding of the enhanced greenhouse among students in the formal classroom setting was conducted by Boyes and Stanisstreet (1992; 1993), who utilized an open-ended written survey completed by 60 students (ages 13-14) to generate a close-ended written survey instrument. This close-ended instrument contained 36 statements divided into three sections dealing with the 1) consequences of a "bigger" greenhouse effect, 2) factors that may make the greenhouse effect "worse," and 3) actions that could make the greenhouse effect "smaller." For each item, students were asked to select one of five Likert-style choices: "I am sure this is right," "I think this is right," "I don't know about this," "I think this is wrong," and "I am sure this is wrong." The instrument was administered to 861 students (ages 11-16) and validated through student interviews (Boyes and Stanisstreet, 1993). This survey (henceforth referred to as the B&S Survey) has since been used verbatim in 4 other research studies involving the following populations:

- 218 British 1st-year undergraduates at a civic university (Boyes and Stanisstreet, 1992)
- 218 British 1st-year undergraduates at the same university almost 10 years later ((Jeffries et al., 2001)
- 702 US secondary students (grades 5-10) (Boyes et al., 1993)
- 330 US undergraduates (elementary pre-service teachers) (Groves and Pugh, 1999)

A subset of the instrument, involving the 12 statements regarding actions to decrease the greenhouse effect, was also administered to 563 British elementary students (ages 8-11) (Francis et al., 1993).

The cross-population and longitudinal use of the B&S Survey has provided insights into student learning about the enhanced greenhouse effect. Comparing undergraduate responses to the survey almost 10 years later, Jeffries (2001) found that the recent undergraduates did slightly worse on all portions of the survey and more frequently selecting the response "I don't know about this."

> Despite an increased certainty about the existence and effects of global warming among experts, the results are broadly similar to, and certainly no better than, those obtained with an equivalent group of students in a previous study, suggesting that despite media publicity and inclusion of the issue of global warming in the formal curriculum, insecure knowledge and misconceptions persist (Jeffries et al., 2001).

Comparing student responses to across age level from ages 11 to 16, Boyes and Stanisstreet (1993) found that British students refined their understanding of the types of human activities that might increase the greenhouse effect. The following statements were selected less frequently by older student: “too much litter in the streets,” “rubbish dumped in rivers and streams,” “radioactive waste from nuclear power stations,” and “acid in the rain.”

Finally, Groves and Pugh (1999) used the B&S Survey to show that many of the misconceptions held by American secondary students (Boyes et al., 1993) were also reported by undergraduate elementary pre-service teachers at a university in Louisiana. Only 5 out of the 36 statements were answered correctly by more than 70% of the pre-service teachers and a third of the questions were answered incorrectly by over 70%. The researchers conclude, “However elementary education majors develop their misconceptions regarding these environmental issues, they are likely to pass along these misunderstandings to their own students” (Groves and Pugh, 1999).

A number of research efforts have been conducted using additional written surveys (both open-ended and close-ended), student interviews, and class observations. Presented first are research studies conducted outside the United States. These are presented here by age level of the students sampled. Koulaidis and Christidou (1999) identified 6 models of student thinking about the enhanced greenhouse effect amongst Greek elementary students using semi-structured interviews, in which student sorted cards listing relevant science concepts. Boyes and Stanisstreet (1997) built off their previous work to develop a more in-depth survey focusing on the enhanced greenhouse effect and the ozone layer that was administered to 501 secondary students (ages 13-14). Andersson and Wallin (2000) created an open-ended survey in Sweden asking students to explain the greenhouse effect, describe how they thought reduction in carbon emissions would impact society, and how they explain why thinning of the ozone layer is a problem. This survey was administered to students in Grade 5 (289), Grade 9 (201), and Grade 12 (n=222). Based in part on this previous study, Papadimitriou developed a 5-item open-ended survey that was given to 172 prospective primary teachers in the 1st year of undergraduate study in Greece. Working in Australia, Fisher (1998a; 1998b) created an 8-item open ended survey inspired by the B&S Survey to differentiate between "life-world" and "scientific" responses and look for changes with age level (ages 10 to 17+). Although the development details are not described, Dove (1996) created a survey instrument for 1st and 2nd year undergraduate pre-service teachers in Britain involving True/False style questions, open response questions, and a prompts for students to create an annotated diagrams to explain the greenhouse effect. In Britain, Spellman (2003) found that British undergraduates performed better on a survey that was originally developed for a reasonably comparable group of undergraduates in the United States (see below, Morgan and Moran, 1995). In a multigenerational study in Canada, Pruneau et al. (2001) showed shifts in thinking between youth to adulthood through analysis of 70 interviews with children (ages 8-9), teens (ages 13-14), and adults (age unspecified).

In the United States, Lester et al. (2006) created a survey that was administered to 611 fifth grade students in Florida. As part of a curriculum unit evaluation, they analyzed pre- and post-instruction responses to a writing prompt and found a correlation between interest in environmental activism and adequate content knowledge. Rye et al. (1997) attempted to use interviews to evaluate the use of concept mapping in a middle-school curriculum used in Pennsylvania (Rubba et al., 1996). A self-reported flaw with this study is that only post-instruction interviews were conducted. Gowda et al. (1997) developed an open-ended survey that was administered to 99 high school students in Hawaii and Oklahoma. In 2003, Khalid modified the survey by Dove (1996) to create a 30-item Likert style survey that was administered to 27 undergraduate students in Missouri pursuing secondary science education. Morgan and Moran (1995) created a 20-item True/False style survey regarding the enhanced greenhouse effect and ozone depletion that was administered to 1382 college undergraduates in a general education environmental science course. In California, Rebich and Gautier (2005) utilized concept mapping software to shed light on pre- and post-instruction understanding of climate change including evidence, causes, mechanisms, consequences, and mitigation. This study involved 17 undergraduates (ages 19-25) enrolled in an upper division geography course. Gautier et al. (2006) recently measured conceptual gains in the same class using a 4-item open-ended survey instrument administered to 8 students pre-, mid-, and post-instruction. Bord et al. (2000), who surveyed 1218 adults in the United States, found that "accurate knowledge of global warming is the strongest single predictor of behavioral intentions." Bostrom et al. (1994) conducted interviews (n=44) and open-ended surveys (n=51) with teens and adults in Pennsylvania and emphasized, "Survey instruments must be based on exploratory work such as these reported here involving interviews and open-ended questionnaires." Based upon this work, Read et al. (1994) developed a 71 item Likert-style survey which was administered to 177 individuals (ages 17-68), also in Pennsylvania.

The largest scale effort that was identified was an international survey sponsored by the George H. Gallup International Institute. This survey was administered to over 6000 adult individuals from 6 countries (Canada, USA, Mexico, Brazil, Portugal, and Russia). This survey included 6 open-ended and forced-choice items that dealt with global warming (Dunlap, 1998).

Another research approach has involved classroom observations. In Italy, Mason and Santi (1998) conducted a study of a fifth grade classroom looking at socio-cognitive interactions and the use of collaborative consensus to impact student understanding. The study presents several examples of students working in small discussion groups to resolve cognitive dissonance through shared insights on the topic of the greenhouse effect. The study also used student interviews to reveal that student ability to reflect upon and recognize personal conceptual change through instruction correlated with post-instruction knowledge. Osterlind (2005) conducted a case study of Swedish 8th grade students elucidating the importance of the textual context of newly acquired information. Osterlind provides several interesting examples in which the student learning was inhibited due to misunderstandings regarding context.

Finally, a number of research efforts in both Britain and the US have focused specifically on student beliefs about ozone depletion and air pollution. These include surveys focusing specifically on the ozone layer and ozone depletion administered to secondary students in Britain (Boyes and Stanisstreet, 1994; 1998) and in Greece (Christidou and Koulaidis, 1996; Christidou et al., 1997; Boyes et al., 1999). In Canada (Leighton and Bisanz, 2003), interviews were conducted with kindergarten, elementary, and adult students regarding the ozone layer. In the US, a pre- and post-instruction survey on the ozone layer was administered to undergraduate pre-service teachers in the US (Groves and Pugh, 2002). Surveys regarding student ideas about the environmental impact of cars and auto-pollution have also been conducted in Britain with both secondary students (Stanisstreet and Boyes, 1997) and undergraduate teacher trainees (Hillman et al., 1996).

1.4.3 Research Findings

Summarized below are some of the central findings of the research efforts described above. First, students do hold some accurate beliefs about the greenhouse effect. These include the ideas that 1) carbon dioxide is involved with the greenhouse effect, and 2) the greenhouse effect increases atmospheric temperatures. High percentages of students have correctly identified CO_2 as an abundant greenhouse gas, including 65% of US undergraduates surveyed by Morgan and Moran (1999) and ~90% of British undergraduates surveyed by Spellman et al. (2003) and ~90% of US pre-service teacher surveyed by Khalid (2003). On various administrations of the B&S Survey, "increased temperatures" was listed most commonly as a consequence of an enhanced greenhouse effect (e.g., Boyes and Stanisstreet, 1992; e.g., Boyes et al., 1993; Groves and Pugh, 1999). In addition, ideas involving trapping of energy were also expressed by students. In all of the B&S Survey studies, students frequently identified that enhancement of the greenhouse effect is caused by the fact that "the Sun's rays cannot escape from the Earth" (e.g., Boyes and Stanisstreet, 1992; Boyes and Stanisstreet, 1993; Read et al., 1994; Fisher, 1998a; Papadimitriou, 2004).

However, it is also clear from the studies above that students also hold seriously inaccurate and incomplete understandings of the greenhouse effect. In addition to CO_2, students frequently mentioned CO, CFCs, and ozone as greenhouse gases (Boyes and Stanisstreet, 1993; Bostrom et al., 1994; Dove, 1996). While technically that latter two gases do have greenhouse characteristics, corroborating evidence suggests strongly that students associate these gases with the greenhouse effect due to a strong association in student minds between the greenhouse effect and ozone depletion. This association was identified in the B&S Survey through student interviews, and also evidenced by high response frequencies to the statements that the greenhouse effect leads to “skin cancer” and would be made worse “by holes in the ozone layer,” “because too many of the Sun’s rays get to the Earth,” and “by CFC gas from spray cans” (Boyes et al., 1993; Boyes and Stanisstreet, 1993; Francis et al., 1993). During interviews and open-ended surveys that asked only about the greenhouse effect, students often independently volunteered descriptions of ozone, the ozone layer, ozone holes, and destruction of ozone. In surveys focusing on the greenhouse effect and ozone depletion, several studies found that students performed better on items related to ozone depletion (Morgan and Moran, 1995; Fisher, 1998a; Spellman et al., 2003) Importantly, but incorrectly, students appear to link the fact that more ultraviolet energy may be entering the atmosphere with overall heating of the atmosphere.

> Within this framework we might easily see how students develop the misconception of the ozone "hole" causing or contributing to the warming of the earth. Based on a student's practical experience, a hole in a protective layer would obviously be the site for some type of "leak." In this case, "rays" from the sun, an obvious source of heat, pour in through the leak [hole]. This will result in a raised temperature for the earth. The

> hole itself is caused by some sort of reaction between "gases" produced by pollution and the ozone is the protective layer. (Meadows and Wiesenmayer, 1999, p237)

Boyes and Stanisstreet (1993) theorize, “Both [the greenhouse effect and ozone depletion] are environmental problems of global dimensions, both are imperceptible to individuals, both are the result of general over-industrialization, and both receive considerable publicity.” Dove (1996) suggests that contributing factors may be scientific uncertainty surrounding the enhanced greenhouse effect issue and the fact that “the greenhouse concept is more complicated to understand, with the absorption of gases being dependent on wavelength.” Kempton (1991) similarly suggests that ozone depletion was the closest available model when the public became exposed to the enhanced greenhouse effect:

> . . . it appears that the ozone hole has arrived as a concept in the US public's consciousness, but the greenhouse effect is entering primarily as a subset of the ozone hole phenomenon, the closest model available.

It has also been shown that many students do not recognize that greenhouse gases are distributed evenly throughout the troposphere; rather, frequently reported student models involve a thin layer of greenhouse gases high in the atmosphere. This probably results from improper associations with the ozone layer and/or the glass of a greenhouse (Dove, 1996; Koulaidis and Christidou, 1999; Papadimitriou, 2004; Gautier et al., 2006). An important aspect of addressing student misconceptions about the greenhouse effect involves differentiating it from ozone depletion. This distinction is addressed on the Greenhouse Effect Concept Inventory (GECI), which contains survey items specifically dealing with the misconception that ozone depletion causes the greenhouse effect.

As mentioned above, students also describe models involving trapping of sunlight in the atmosphere (e.g., Boyes et al., 1993; Read et al., 1994; Boyes and Stanisstreet, 1997; Fisher, 1998b; Papadimitriou, 2004; Rebich and Gautier, 2005). However, this description, which more accurately represents the greenhouse effect, often accompanies explanations of more sunlight entering through holes in the ozone or the ozone layer letting more light in but less light out of the atmosphere (e.g., Papadimitriou, 2004; Rebich and Gautier, 2005). It has also been found in a number of studies that students associate the greenhouse effect with pollution and air pollution (e.g., Bostrom et al., 1994; Stanisstreet and Boyes, 1997; Koulaidis and Christidou, 1999; Papadimitriou, 2004; Rebich and Gautier, 2005). Bostrom et al. (1994) found that incorrect student definitions of the greenhouse effect and ozone depletion were most often matched with expert definitions of "air pollution problems."

Students also misunderstand the distinction between climate and weather, failing to recognize that climate involves characteristics measured of long periods of time (e.g., Bostrom et al., 1994; Spiropoulou et al., 1999). It has been shown that students typically use personal experience with local weather conditions as primary evidence for global warming (Kempton, 1991; Gowda et al., 1997; Papadimitriou, 2004) Perceptions of recent heat waves and shorter, less snowy winters were cited by respondents rather than the rigorous scientific monitoring of yearly temperatures around the globe. Another finding is that students and public often *overestimate* the amount of warming that is predicted to occur due to global warming (Bostrom et al., 1994; Read et al., 1994; Gowda et al., 1997).

Many of the studies in the literature focus more heavily on environmental aspects related to the enhanced greenhouse effect. However, a handful probe deeper into student conceptions of the physics associated with the greenhouse effect. In particular, Andersson and Wallin (2000) and Kouladis (1999) have used open-ended written surveys and interviews, respectively, to elicit mental models of the greenhouse effect. Andersson and Wallin, for example, describe and diagram 5 mental models: 1) that more of something in the atmosphere makes it warmer, 2) that more light enters the atmosphere (often through holes in the ozone), 3) that heat in the atmosphere does not escape to space and bounces back to the Earth (with no reference to where the heat originated), 4) that incoming energy does not get back out (incoming and outgoing energies are the same), and 5) the most complete model in which the incoming and outgoing energies are different. Indicative of students' incomplete knowledge, these models and the literature in general do not generally provide references to energy ever leaving the Earth system to space. Working with Australian secondary students, Fisher describes that "heat balance and equilibrium notions has almost nil representation, probably due to the sophistication and unfamiliarity of the arguments involved there" (1998a). Several studies have also noted that students tend to conceptualize energy trapped in the atmosphere or energy leaving the atmosphere as being reflected solar energy rather than radiated terrestrial energy (Dove, 1996; Papadimitriou, 2004; Rebich and Gautier, 2005; Gautier et al., 2006). Finally, it has been noted that students do not differentiate well between ultraviolet rays and solar or thermal rays and easily attribute "thermal properties to ultraviolet rays, suggesting that they are extremely strong, hence very hot" (Christidou and Koulaidis, 1996). As Rye et al. (1997) point out:

> . . . Learners will bring to global warming instruction the intuitive knowledge that the Sun feels warm and that a sunburn makes us hot. Such intuitive knowledge can interact with new information to yield unintended outcomes, e.g. the alternative conception that the extra sunlight or ultraviolet radiation, coming though the 'hole' in the ozone layer, heats up the planet.

This is likely a fundamental aspect of students' association between ozone depletion and increased atmospheric temperature. Central concepts covered on the GECI include the concept of energy balance and the types of energy absorbed and given off by Earth's surface and atmosphere.

Implications for Greenhouse Effect Education

The conflation of the greenhouse effect, ozone depletion, and air pollution has been widely discussed with speculation on why these ideas are commonly intermixed. One suggestion is that "global warming lacks the simple and highly symbolic signal conveyed by the computerized map of the 'hole' in the ozone layer" (Dunlap, 1998). More commonly discussed factors are that each of these are environmental phenomena that involve the atmosphere, are largely invisible and imperceptible, involve gases (including CFCs), and are mostly informed through the media and informal education channels (Boyes and Stanisstreet, 1992; Francis et al., 1993; Bostrom et al., 1994; Gowda et al., 1997; Dunlap, 1998).

> We suggest that such misconceptions may have their origins in an erroneous generalization, or even fusion, of ideas in the minds of children. For example, children may distinguish generally between major environmental problems such as global warming and ozone layer depletion but fail to separate mentally the mechanism involved.

> Alternatively, young people may employ a single construct, ‘environmental problems,’ in which the issues themselves are fused. (Francis et al., 1993)

This can lead to a form of “fuzzy environmentalism” (Gowda et al., 1997) in which students lump together environmental causes, consequences, and actions.

Francis et al. (1993) found high response frequencies among very young students (age 8) for statements that the greenhouse effect could be decreased through cleaning up beaches (>70%) and nuclear disarmament (>80%). Interestingly, one misconception that was especially resistant to change across all age levels was the idea that using unleaded petrol would decrease the greenhouse effect (Boyes and Stanisstreet, 1992; Boyes and Stanisstreet, 1993; Francis et al., 1993). Francis et al. (1993) also propose that students “develop an understanding that the environment is ‘good,’ and whatever threatens the environment is obviously ‘bad.’” This finding is consistent with student understanding of other naturally occurring phenomena that have been deemed uniformly as bad, such as nuclear radiation (Prather, 2000; Prather and Harrington, 2001). Bostrom et al. (1994) reinforces this through finding that 75% of US teen and adult respondents expressed that the greenhouse effect was “bad in general.” Similarly, Boyes and Stanisstreet (1992) argue that students approach environmental issues subjectively:

> We suggest that there is a general awareness of a range of environmental problems, from the local to the global, and a variety of environmentally “friendly” and “unfriendly” actions. However, it appear that many students do not link particular problems with their particular causes, consequences and solutions; rather there appears to be the general idea that almost all environmentally "friendly" actions help all problems.

Ironically, a close inspection of the S&S Survey shows that these same researchers actually reinforce the good-bad dichotomy through the use of the stem “The Greenhouse

Effect is made worse by . . .”. This statement implies that the Greenhouse Effect is already bad!

Student beliefs that the greenhouse effect is “bad” is also likely related to the fact that scientists, science educators, and the media commonly use the term “greenhouse effect” to refer to the “enhanced greenhouse effect” or “global warming.” Kempton (1991) explicitly describes “We chose this term [the greenhouse effect] over ‘global warming’ or ‘global climate change’ as more commonly used by the media and more widely recognized by the public.” Rye et al. (1997) clarified to interview participants that the terms “greenhouse effect” and “global warming” were equivalent. Only and handful of studies have directly investigated the question of whether students understand that natural greenhouse warming contributes to a generally warmer planetary surface temperature. Dove (1996) found that the British undergraduates she sampled were split on whether the greenhouse effect is important for life. Additionally, of those who thought that it was, only 1 in 5 explained that it was important due to planetary warming and 10% described that the greenhouse effect provides a protective barrier. Andersson and Wallin (2000) found only 10% of the Swedish students surveyed clearly referred to a natural greenhouse effect in open-ended responses. The remaining responses described either an enhanced greenhouse effect, ozone depletion, or both. Morgan and Moran (1995) noted that only a third of US undergraduates surveyed identified clouds and water vapor as greenhouse agents and point out that “atmospheric scientists need to do a better job of communicating” a distinction between the natural and enhanced greenhouse effect.

Several survey items on the GECI instrument described in this work address student distinctions between the greenhouse effect and global warming.

A number of educational strategies have been proposed for addressing the inaccurate, incomplete, and intermixed ideas discussed above. The summary below samples just some of these. Several papers emphasize that misconceptions develop early and that it is important to emphasize to young children that there are different types of environmental problems rather than one single environmental construct. Francis et al. (1993) recommend providing "at an early age a catalog of different and 'separate' environmental problems that humankind faces. Later, their interlocking causes and consequences could be revealed." Read et al. (1994) suggest that both the media and formal curricula not report on the greenhouse effect and ozone depletion together and in the same printed graphics. However, Rye et al. (1997) disagree with separating the two topics in a curriculum, stating "a directive to avoid the topic of ozone while teaching about global warming is impractical and may not be conducive to helping students restructure related alternative conceptions." They argue that the environmental issues are separate but related and that contrasting the two is important for emphasizing the distinctions. They and others (Rebich and Gautier, 2005; Gautier et al., 2006) also emphasize that the difference between incoming and outgoing radiation must be reinforced.

Several researchers (e.g., Pruneau et al., 2001; Papadimitriou, 2004) suggest small group discussions to break down student misconceptions. Pruneau et al. (2001) refer to this approach as a "socio-constructivism." Others have emphasized that in addition to identifying and breaking down misconceptions, it is necessary to "provide a more correct replacement for the misconception" (Meadows and Wiesenmayer, 1999). They suggest both "Socratic" dialogue between teachers and students and "social discourse taking place in peer discussions." Others have suggested the use of computer environments for facilitating learning (Cavalli-Sforza et al., 1994).

Finally, a number of curriculum materials have been created to address student understanding of the greenhouse effect (e.g., Hoppenau, 1992; Rubba et al., 1996; Mak, 1997; Rye et al., 1997; Rye and Rubba, 1998; Dunnivant et al., 2000; Papageorgiou and Ouzounis, 2000; Lueddecke et al., 2001; Browne and Laws, 2003; Rebich and Gautier, 2005; Lester et al., 2006). Although a thorough review of these works is not provided here, it is noted that these activities include an assortment of activities ranging from analysis of historical atmospheric data, experimentation regarding absorption properties of water, class debates regarding causes, consequences, and solutions to the climate change, and modeling of the greenhouse effect through use of glass aquaria. Interestingly, only three of the papers listed above attempt to measure the influence of instruction. Lester et al. (2006) utilized open-ended student writing samples; Rebich and Gautier (2005) analyzed pre- and post-instruction student concept maps; Rye and Rubba (1998) utilized both interviews and concept mapping. As described below, the lack of a quantitative instrument for measuring the effectiveness of instructional strategies addressing the greenhouse effect was a motivation for the development of the Greenhouse Effect Concept Inventory (GECI).

1.4.4 Role of the GECI

As evidenced above, significant effort has already been focused on student understanding of the enhanced greenhouse effect in Europe, the United States, and Australia. In addition to adults, these studies have involved elementary, secondary, and undergraduate students using interviews, open-ended surveys, close-ended surveys, and classroom observations. How, then, does the GECI contribute to this already rich field of study?

First, it is important to note that only six previous studies have involved post-instruction evaluation efforts. One of these (Rye et al., 1997) neglected to conduct any corroborating pre-instruction data. Two of the studies involved fifth grade students, using interviews in Italy (Mason and Santi, 1998) and open-ended student writing samples in Florida (Lester et al., 2006). The remaining three studies involved 58 pre-service teachers in Louisiana (Groves and Pugh, 2002) and less than 20 college geography students in California (Rebich and Gautier, 2005; Gautier et al., 2006). The GECI has been developed as a diagnostic test to measure pre- and post-instruction conceptual gains with large samples of students. In the development phase alone, the GECI was administered to over 1800 students pre- and post-instruction. It is also the only multiple-choice concept inventory found in the literature specifically designed to elicit student beliefs on the greenhouse effect. The instrument was validated through analysis of written explanations of reasoning to preliminary multiple-choice items, interviews with undergraduate students, and an expert review by professionals in planetary science (graduate students and professors).

Second, only six of the studies in the literature involved undergraduate students in the United States. Three of these targeted pre-service elementary and secondary science teachers (Groves and Pugh, 1999; 2002; Khalid, 2003) and two involved an upper-division geography course (Rebich and Gautier, 2005; Gautier et al., 2006). Only the research effort by Morgan and Moran (1995) involved students comparable to those used for development and testing of the GECI. Morgan and Moran surveyed a large number of students (n=1382) using a True/False style survey with 10 items on the greenhouse effect and 10 items on ozone depletion.

However, similar to many of the studies discussed above, the items on the Morgan and Moran (1995) survey focus largely on consequences of and agents contributing to an *enhancement* of the greenhouse effect. Only two studies specifically probed whether students recognized that there is a natural greenhouse effect (Dove, 1996; Andersson and Wallin, 2000). The GECI focuses more closely on important conceptual aspects regarding the physics of the natural greenhouse effect, including the types of energy flowing through Earth's atmosphere and the concept of energy balance. Results from the GECI provide additional data involving a large sample of undergraduate non-science majors at a research university in the southwestern US that is useful to inform and corroborate with previous findings within the literature.

Finally, the GECI is one of a number of recent concept inventories that have been recently developed in the field of physics and astronomy education research. A concept inventory is a multiple-choice style instrument focused on a specific topic and based upon known student misconceptions. Concept inventories are useful for assessing pre-and post-instruction conceptual understanding on a specific topic. The most widely used concept inventory in physics education research is the Force Concept Inventory (FCI) (Halloun and Hestenes, 1985; Hestenes et al., 1992), which deals with force and motion and has been administered to tens of thousands of physics students over the past two decades. Additional concept inventories have been recently developed on lunar phases (Lindell, 2001; Lindell and Olsen, 2002), properties and formation of stars (Bailey, 2006), light and spectroscopy (Bardar et al., 2005; Bardar, 2006), natural selection (Anderson et al., 2002), and biology (Klymkowsky, 2006). It is hoped that the GECI will be adopted as an education research tool in earth and planetary science, atmospheric science, and astronomy.

1.5 Goals of Project and Organization of Dissertation

Many of the studies described above involved research into student beliefs related to the enhanced greenhouse effect and were pursued from an environmental education perspective. Of those that focused in more detail on student misconceptions regarding the physics of the greenhouse effect, very few dealt with the understanding amongst undergraduate non-science majors at the university level in the United States. As a research project in planetary science education, the study presented here focuses more on understanding of the physics of energy transfer through greenhouse atmospheres within this population of students.

Student beliefs and reasoning difficulties related to the greenhouse effect were elicited using a mixed-method study involving written surveys, interviews, and instructional interventions administered over six semesters between Fall 2003 and Spring

2006. Three different styles of written surveys were utilized. Student-Supplied Response (SSR) surveys asked students to provide written responses to open-ended prompts which provided minimal to no background information on the topic. Multiple-Choice (MC) surveys instructed students to select the best answer from a list of up to five choices per survey item. Multiple-Choice with Explanation of Reasoning (MCER) surveys combined the previous two formats and tasked students to provide written explanations of their reasoning for multiple-choice item selections. Finally, student interviews were conducted in which students explained the reasoning behind their choices to MC items. The final concept inventory resulting from this work, the Greenhouse Effect Concept Inventory (GECI.vC), consists of 20 multiple choice questions regarding the greenhouse effect, global warming, and the flow of energy through Earth's atmosphere.

Student beliefs identified through analyses of SSR surveys are presented thematically in Chapter 2. These results were used to guide the development of the GECI, which is described in Chapter 3 along with further insights gained from student written explanations and interviews. Chapter 4 focuses on validation of the GECI instrument using standard tests and measures as well as an expert review process. This chapter also describes a preliminary investigation into the use the GECI to discriminate between learning gains associated with varying educational interventions regarding the greenhouse effect. Finally, Chapter 5 turns to a second research project involving gamma ray data collected from Mars. Further explanation of how this research project complements the graduate experience of the author is provided at the beginning of Chapter 5.

CHAPTER 2: BELIEFS BASED UPON STUDENT-SUPPLIED RESPONSE (SSR) SURVEYS

2.1 Context and Setting

Student beliefs and reasoning difficulties regarding the greenhouse effect were surveyed at the University of Arizona, a research university in the southwestern United States enrolling over 28,000 undergraduate students and more than 8,000 professional and graduate students. Approximately 53% of these are female and 47% male. The majority of undergraduate students are Caucasian (65%), with Hispanic students making up the second largest ethnic grouping (15%). Other reported ethnicities make up 14% of the undergraduate population and data is not available for the remaining 6%. Most undergraduate students are between ages 18-21 and the attrition rate between the first and second year for undergraduates is ~24%.

All students subjects were undergraduates enrolled in introductory science courses for non-science majors as part of the university's general education requirement. Non-science majors at the university are required to take two different introductory science classes (termed Tier 1) during their undergraduate career along with one sophomore level science class (Tier 2). These classes can be selected from a diverse offering of roughly 70 courses taught by science departments throughout the campus. The study focused primarily on courses offered in planetary science, atmospheric science, astronomy, and global change, although a few life science and chemistry classes were involved as pseudo-control groups. These courses typically enroll between 100-150 undergraduate students (although some classes enroll up to 300) and are typically taught in a traditional lecture-based, theater-style environment. Although minimal to no laboratory-based experiences are included in these classes, some classes incorporated learner-centered small-group activities. Data was collected between Fall 2003 and Spring 2006.

2.2 Description of SSR Survey Instruments

As described in Section 1.5, Student-Supplied Response (SSR) surveys were used to elicit student beliefs and reasoning difficulties related to the greenhouse effect. These surveys asked students to provide written responses to open-ended prompts. These prompts were designed to provide minimal to no background information to avoid biasing student thoughts and ideas on the topic. The intent was to gather qualitative data presented in student language as a basis for designing a more quantitatively robust Greenhouse Effect Concept Inventory (GECI).

An overview of the SSR surveys in this study is provided on Table 2.1. This table lists the semester that each survey was administered, the number of classes that participated, and the number of students surveyed pre- and post-instruction. Copies of SSR survey instruments are provided in Appendix A.

Table 2.1 Summary of SSR survey instruments

Survey Label	Description	Semester	Number of Classes	Number of Surveys Collected	
				Pre	Post
SSR.vA	1-part SSR question Describe what GHE is and how it occurs	Fall 2003 Spring 2004	4	558	310
SSR.vB	3-part SSR question Describe and distinguish between GHE, O_3 depletion, and GW	Spring 2004	1	115	108
SSR.vC1	3-part SSR question Identify and describe characteristics of GH gases	Spring 2005	6	61	28
SSR.vC2	1-part SSR question Clarify distinction between GHE and pollution	Spring 2005	6	58	33
SSR.vC3	3-part MC/SSR question Select and describe an analogy for the GHE	Spring 2005	6	52	19
SSR.vC4	2-part SSR question Diagram and describe how VIS & IR interact w/ atmosphere	Spring 2005	6	57	31
TOTAL			11	901	529

The initial survey of this study (SSR.vA) was administered to two introductory astronomy classes during Fall 2003 and an introductory astronomy class and introductory atmospheric science class during Spring 2004. For this survey, each student was asked to supply a written response to an open-ended prompt asking them to describe what the greenhouse effect is and the science behind how it occurs. The survey was administered both before and after instruction on the topic of the greenhouse effect in each class. The SSR.vA surveys were analyzed and coded iteratively as described in Section 2.2.1 below. Preliminary quantitative and qualitative results of this survey led to the development of the additional SSR survey versions listed in Table 2.1.

2.2.1 Preliminary SSR Survey (SSR.vA)

At the outset of the project, an open-ended survey (SSR.vA) was administered in two sections of an introductory astronomy course during Fall 2003 both before and after instruction. Students were asked to take out a blank sheet of paper and were given ten minutes to provide written responses to the following prompt which was displayed in the front of the classroom:

> You've heard about the Greenhouse Effect before, but what is it really? Describe in as much detail as possible what you think the Greenhouse Effect is and the science behind how it occurs.

The purpose of this survey was to gain preliminary insight into beliefs, ideas, and concepts that students hold with regard to the greenhouse effect presented in student language without introducing bias from the wording of survey items. A preliminary reading of the 360 pre-instructional student responses confirmed that these survey forms contained a rich set of diverse student beliefs and ideas about the greenhouse effect and the flow of energy through Earth's atmosphere.

During Spring 2004, the same survey prompt was administered to an introductory astronomy course and an introductory atmospheric sciences class both before and after instruction. During this second administration of SSR.vA, each student was provided a photocopied sheet of paper with the same prompt question listed above (see Appendix A). The following prompt was also added at the end of this, "Please provide a sketch if possible." An additional 198 pre-instructional surveys were acquired from this second administration effort, bringing the total number of SSR.vA survey forms to 558.

During the Spring 2004 semester, SSR.vA forms from all four classes were analyzed through an iterative coding process described below. First, a subset of ~100 pre-instructional forms from one of the Fall 2003 astronomy courses were analyzed and a coding schema for the concepts expressed was created. These student-supplied concepts were arranged into the following thematic categories:

1) Gases: specific gases identified by students
2) Sources: natural and human/artificial sources for those gases
3) Consequences: consequences of the greenhouse effect on the atmosphere, oceans, land, life, and humans,
4) Harmful/Beneficial: descriptions of the greenhouse effect as either a harmful or beneficial process
5) Student Models: student models regarding the mechanism by which the greenhouse effect works
6) Light Interactions: descriptions of ways light interacts with the atmosphere
7) Analogies: analogies provided for the greenhouse effect
8) GHE/GW/O3: the relationship between the greenhouse effect, global warming, and ozone depletion
9) Energy Flow: types of energy flowing into, out of, and being trapped by Earth's atmosphere

Survey forms from each of the four classes surveyed were then coded. During this process, a new concept or idea would appear occasionally on a student form that was not represented on the coding schema. These new concepts were added iteratively to the schema. Thus, while the initial coding schema had 116 items grouped within the nine-themes listed above, at the end of the process the schema consisted of 168 items. It is important to note, however, that the added concepts were encountered very infrequently. Indeed, only ten of the added concepts occurred at frequencies greater than 1% of all subsequently coded survey forms (with a maximum frequency of 3.6% for oxygen gas as being a greenhouse gas). Appendix B provides copies of both the initial and final coding schemas.

Several central beliefs and ideas were identified through coding of the pre-instruction SSR.vA survey. These are outlined in Table 2.2 below and described in more detail throughout the remainder of the chapter.

Table 2.2 Student beliefs and ideas regarding greenhouse effect (SSR.vA)

1.	The greenhouse effect involves extra energy entering and heating Earth's atmosphere due to thinning or destruction of the atmosphere. - Ultraviolet light and "harmful rays from the Sun" were often referenced. - Ozone, the ozone layer, ozone depletion, and ozone holes were commonly identified as the component of the atmosphere affected.
2.	The greenhouse effect involves something being trapped inside Earth's atmosphere causing an increase in atmospheric temperatures. - Student models include both the trapping of energy and light and the trapping of gases, gas molecules, and pollution. - Student most often refer to trapping of "heat," but some students describe of heat as a form of energy while others describe it as a substance. - Common trapping agents are greenhouse gases, pollution, the ozone layer, and clouds. - The predominant trapping mechanism involves "bouncing" or "reflection." - Trapping model often involves permanent trapping with little or no release to outer space.
3.	The greenhouse effect involves both of the above mechanisms: more is entering the atmosphere and also being trapped. - Frequent references to the ozone layer both allowing more to enter and trapping more
4.	Other mechanisms are also involved in the greenhouse effect. - Descriptions included circulation and convection of air, the water cycle, photosynthesis, the carbon cycle, and magnification and concentration of light passing through the atmosphere.
5.	The greenhouse effect is caused by gases given off by human activities. - Carbon dioxide was most frequently cited as a greenhouse gas - "Pollution" and "chemicals" identified as the main causes of the greenhouse effect
6.	The greenhouse effect causes increased planetary temperatures - Other consequences included melting of polar ice caps, rise in sea level, damage to plants and animals, and skin cancer
7.	The greenhouse effect is like a plant greenhouse, which helps plants grow. - Plant greenhouses block some things and trap others - Some students referred to plant greenhouses as trapping energy. - Some students referred to plant greenhouses as trapping gases. - Other common analogies included a blanket and a shield.
8.	The greenhouse effect is associated with "global warming" and "ozone depletion." - Students often referred to these other environmental phenomena by name. - Students often described the greenhouse effect with descriptions better suited to global warming or ozone depletion. - Students often expressed that the greenhouse effect had a negative connotation: it is "damaging" or "bad for the environment."

2.2.2 Follow-up SSR Surveys (SSR.vB and SSR.vC)

Five additional student-supplied response surveys were administered during Spring 2004 and Spring 2005. Each of these provided prompts to focus student responses on specific aspects of the greenhouse effect that had been identified through coding of SSR.vA.

In agreement with previous research (e.g., Boyes and Stanisstreet, 1993; Francis et al., 1993; Bostrom et al., 1994; Dove, 1996; Gowda et al., 1997), coding of Survey SSR.vA revealed that students often provided responses more closely aligned with ozone depletion and global warming than with the natural greenhouse effect. Survey SSR.vB was administered during the middle of the Spring 2004 semester to students enrolled in an introductory planetary science course to address this issue further. Survey SSR.vB (see Appendix C) asked students to describe and distinguish between each of these concepts using the following prompt provided on a photocopied sheet of paper:

> You've heard about "Ozone Depletion," the "Greenhouse Effect," and "Global Warming," but what are these really? Describe in as much detail as possible your conception of what each of these atmospheric phenomena is. How are they related or not related to each other? Please provide sketches if possible.

Survey SSR.vB was analyzed by reading through responses to each of the concept prompts separately and looking for themes and patterns.

During Spring 2005, four different versions of survey SSR.vC were administered to six introductory science courses. Copies of these surveys are provided in Appendix D. To more carefully quantify student beliefs about greenhouse gases, Survey SSR.vC1 asked students to list the primary greenhouse gases and describe the main characteristics that make them greenhouse gases. It also asked students whether they thought that greenhouse gases are visible to the naked eye in an attempt to distinguish between particulate pollution and greenhouse gases. Based upon frequent references connecting the greenhouse effect to pollution on Survey SSR.vA and in previous research (e.g., Bostrom et al., 1994; Boyes and Stanisstreet, 1997; Koulaidis and Christidou, 1999), Survey SSR.vC2 asked students to clarify what type of pollution they think leads to the greenhouse effect. Using analogies identified through coding of Survey SSR.vA, another follow-up survey was developed to quantify which analogies were most popular among students (SSR.vC3). Finally, Survey SSR.vC4 provided a structured opportunity for students to diagram the flow of visible and infrared light through Earth's atmosphere. This provided a standardized template for comparing student diagrams in a manner not possible with Survey SSR.vA. Surveys SSR.vC1-4 were analyzed to find patterns and trends clarifying student thinking regarding the topic of the specific survey prompt. Findings from these analyses are included in the relevant discussion sections below regarding central beliefs identified through coding of Survey SSR.vA (see Table 2.2).

2.3 Models Involving Increase in Energy Entering Atmosphere

One of the most common explanations presented on SSR.vA surveys is that the greenhouse effect is caused by an increase in the amount of energy entering Earth's atmosphere due to thinning, deterioration, or destruction of part of the atmosphere. Students reason that if energy that typically is blocked by the atmosphere is allowed to enter, this will lead to increased temperatures. While student responses did not always indicate the type of energy or component of the atmosphere involved, students clearly described that a thinning or deterioration of the atmosphere was letting more energy in and heating the Earth:

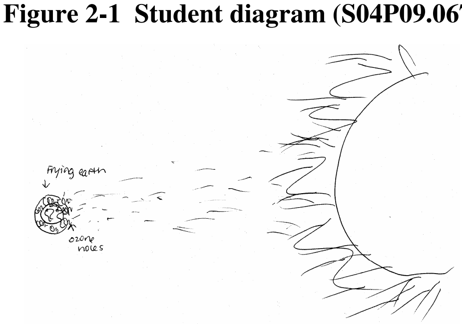
> I think that the greenhouse effect has to do with the Earth's atmosphere is slowly getting thinner in spots and so it creates much warmer Sun and all rays are much stronger. (F03P07.153)

> I think that the greenhouse effect has something to do with the deterioration of the Earth's atmosphere. When the atmosphere is completely deteriorated there will be nothing to prevent harmful light waves from reaching us. I'm not really sure how it occurs but I think it has something to do with pollution. Maybe somehow the contamination of the air eats away at our atmosphere. (F03P07.067)

Out of the 558 students who completed SSR.vA, 186 (33%) explicitly referenced the ozone as being part of the greenhouse effect. Of these, 63% (n=117) provided descriptions indicating that they thought the ozone or ozone layer was being depleted or destroyed, or that holes were being formed in the ozone, leading to an increase in the amount of energy entering Earth's atmosphere. The student responses and diagram below provide examples:

> I think that it has something to do with the ozone layer and how it is slowly "going away." Pollution is the cause of this. The ozone is what helps keep out some of EM radiation and this radiation is harmful to living things. So the greenhouse effect is how the ozone layer is depleting. There are thoughts that everything will burn when the ozone layer is gone. (F03P06.091)

Figure 2-1 Student diagram (S04P09.067)



> The lessening of plants and the increase of CO_2-producing objects is causing a gradual warming of the Earth. Also, particles that destroy the ozone create holes, which also warms the Earth. (S04P09.067)

Out of the 186 students who mentioned ozone, 109 students (59%) specifically identified ultraviolet energy as the type of energy that is entering through the ozone layer as it is depleted. The student quote below provides an example of this:

> The greenhouse effect is due to the deterioration of the atmosphere around the poles because of pollution and CFC's. This deterioration causes more UV light because we are left with less protection from the atmosphere, and this, in turn, is causing the Earth's temperature to slowly increase. This causes the seasons to change with the warmer climate. (F03P07.010)

It is apparent from analysis of SSR.vA surveys that many students base their understanding of the greenhouse effect squarely on concepts more appropriately associated with the separate environmental phenomenon of ozone depletion. This finding is in agreement with several previous studies described in Chapter 1 (e.g., Boyes and Stanisstreet, 1992; Boyes et al., 1993; Francis et al., 1993; Meadows and Wiesenmayer, 1999).

Students also provided insights into why they associate the greenhouse effect with the ozone layer. These included references to sunburns and skin cancer and the importance of wearing sunscreen and sunglasses as protection from damaging ultraviolet rays. Student described that they had learned this from the news, from watching TV, from advertisements, from teachers, and from hearing "what everyone talks about." Students have assimilated this information as part of their reasoning regarding increases in global temperatures:

> I think the greenhouse effect is the warming and erosion of Earth's atmosphere. Somehow pollution causes erosion of Earth's atmosphere.

> The erosion of the atmosphere allows different rays to reach Earth that normally would not. In turn this causes all kinds of problems: people are more susceptible to skin cancer and Earth's temperature begins to rise. (S03P07.032)

> I have been told throughout school, and even some public service announcements, a lot about how we are in "danger" from "global warming" and the greenhouse effect. Yet basically, all the information that I got was that hairspray and CFC's in refrigerators destroy ozone and cause the Earth's surface to heat up. (S03P06.103)

2.4 Models Involving Trapping of Energy or Matter in Atmosphere

2.4.1 Trapping of Energy or Matter

A second common explanation for the greenhouse effect involves "trapping" of something in the atmosphere. Out of the 558 students surveyed in SSR.vA, 277 (50%) described that trapping of heat, energy, light, gases, humidity, pollution, or clouds was involved with the greenhouse effect. It is important to emphasize that students described several different entities as the things that are actually trapped by the greenhouse effect. By no means did students commonly describe infrared light given off by the heated surface of the planet as the thing that interacted with greenhouse gases. Table 2.3 provides a summary of common phenomena that were identified as being trapped by the greenhouse effect.

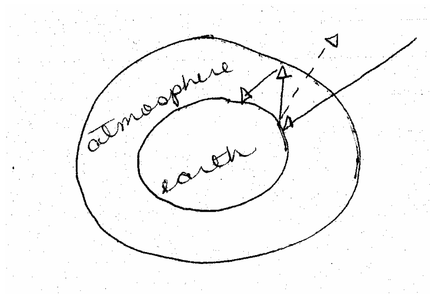
Table 2.3 Descriptions of what is trapped (SSR.vA)

Description of Entity Being Trapped	Number of Students	Percent of Surveys (n=558)	Percent of Surveys Describing Trapping (n=277)
Heat, warmth	101	18.1%	36.5%
Light, radiation, electromagnetic radiation	95	17.0%	34.3%
Gases, gas molecules, pollution	70	12.5%	25.3%
Energy	33	5.9%	11.9%
Sunlight	32	5.7%	11.6%
Ultraviolet light	23	4.1%	8.3%
Infrared light	15	2.7%	5.4%
Moisture, humidity, clouds	13	2.3%	4.7%
Long-wave radiation	2	0.4%	0.7%
Visible light	1	0.2%	0.4%
X-ray	1	0.2%	0.4%
Gamma Rays	1	0.2%	0.4%

As the table shows, “heat” and “warmth” were the most common descriptions of what is trapped by the atmosphere (n=101). However, as discussed later in this section, it was often unclear what students meant by these terms. The next most popular trapping responses involved generic descriptions of energy, in the form of light and electromagnetic radiation (n=95), or matter, in the form of gases, gas molecules, and pollution (n=70). Before turning to student representations of heat and warmth, descriptions of trapping of energy and matter are discussed separately below.

Models involving trapping of energy are discussed first. Out of the 277 surveys that described trapping models, 49% (n=137) provided generic descriptions of the trapping of energy, sunlight, and/or light. Students were less specific about actual types of trapped light, but ultraviolet light (n=23) followed by infrared (n=15) were listed most frequently. Combining generic descriptions of and references to specific types of light results in 163 surveys (59%) that describe energy as being trapped. The student response and diagram below provides an example of energy and light being trapped:

Figure 2-2 Student diagram (F03P07.062)



> The greenhouse effect is when the rays of light from the Sun bounce off Earth like they are supposed to but don't get past our atmosphere (which isn't supposed to happen) then they are trapped as is their energy and therefore the temperature of the Earth is heating because of the energy trapped. (F03P07.062)

In the student diagram above, the dashed arrow represents the flow of energy if Earth's greenhouse effect did not trap the energy in the atmosphere. The diagram clearly shows rays of light (solid arrows) being confined to the atmosphere. Additional references to light and energy being trapped are provided below:

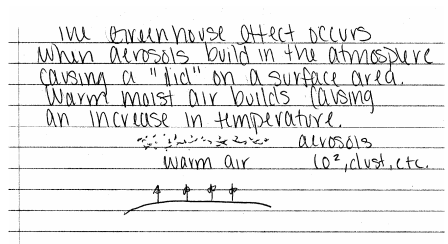
> The greenhouse gases trap light and energy to make our planet warm. Without greenhouse gases our planet would be an ice ball. (F03P06.124)

> The greenhouse effect is sort of when sunlight passes through and is trapped into an area. By trapped, I mean the sunlight gets into an enclosed area, and the heat produced by the sunlight cannot escape, so it keeps the enclosed area warmer and warmer. (F03P06.083)

However, more than 25% of the students with trapping models (n=70) described that the greenhouse effect involves the trapping of substances. Common examples included gases, gas molecules, pollution, moisture, humidity, and clouds. Here students describe that the greenhouse effect traps matter within the atmosphere rather than energy:

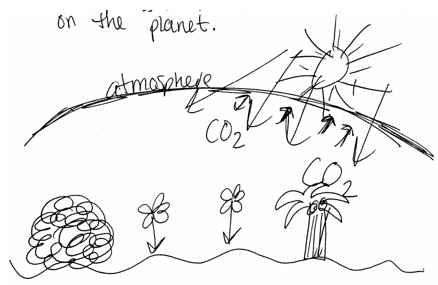
> I understand the greenhouse effect with this picture. Pollution rises into the Earth's atmosphere but there is a "glass roof" that causes the pollution to remain in the atmosphere because the dirt and smuck never leaves the atmosphere. (F03P06.085)

Figure 2-3 Student diagram (S04M53.012)



> The greenhouse effect occurs when aerosols build in the atmosphere causing a "lid" on a surface area. Warm moist air builds causing an increase in temperature. (S04M53.012)

Figure 2-4 Student diagram (S04P09.029)



> The greenhouse effect makes our atmosphere what it is. It holds in the CO_2 of our planet. When gases enter our atmosphere many of them also leave, but the greenhouse effect keeps some of these in (esp. CO_2) so we can maintain life on the planet. (S04P09.029)

Each of the descriptions and diagrams explicitly describes matter (pollution, dirt, warm moist air, and CO_2) as being trapped. In some student minds, one consequence of this trapping of matter is that the atmosphere becomes thicker and denser:

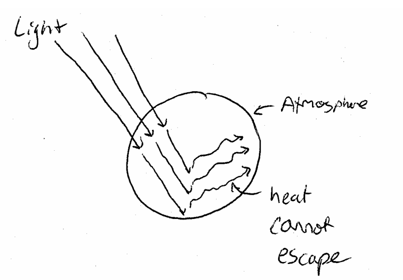
> The greenhouse is when gasses are too dense to escape our atmosphere, they become trapped and cause the Earth to increase in temperature because then Sun light is not able to penetrate back out of the Earth's atmosphere. (F03P07.168)

> The greenhouse effect is dealing with global warming. As more pollution is added to the air, clouds become dense and trap warm air. This air gets sucked into the vicious cycle of "the greenhouse effect." (S04M53.028)

Returning to the most common response on surveys, 101 students described that "heat" or "warmth" is trapped by the atmosphere. The following student quotes illustrate this student belief:

> Extra amount of carbon gas such as CO_2, mainly caused by oil consumption, forms the layer in the atmosphere, and it prevents the heat from escaping outside the Earth and raises the temperature over the world. (F03P06.170)

Figure 2-5 Student diagram (S04P09.073)



> The greenhouse effect is when the rays of the Suns light enters our Earth and cannot escape due to high amounts of CO_2 and low amount of O_3 in the atmosphere. The light produces heat and the heat gets trapped because of the CO_2. (S04P09.073)

However, it is unclear whether students envisioned heat as a form of energy, the transfer of energy, or as a substance. Previous research has shown that students have poorly defined conceptions of heat and often think of it as a thing or substance that is transported through a medium rather than the more precise definition of heat involving the flow of energy from hot to cold (Erickson and Watts, 1985). Insight can be gained into this question by comparing the number of students who associated heat and energy (or light) and the number of students whose written responses described heat with a substance. Table 2.4 below shows the breakdown of cases that described the trapping of heat.

Table 2.4 Heat as form of energy or matter (SSR.vA)

Description of Heat	Number of Students	Percent of Surveys (n=101)
Heat with no description	51	50%
Heat with description of energy being trapped	29	29%
Heat with descriptions of matter being trapped	19	19%
Heat with description of both energy and matter being trapped	2	2%

As the table shows, 50% the students (n=51) did not provide a description of what they meant by heat. Of the remaining 50 students, roughly 58% (n=29) associated heat with energy, 38% (n=19) associated heat with matter, and 4% (n=2) described both energy and matter along with heat. The quotes below provide examples of each of these categories. The first response provides an example of a student who discusses heat as a form of energy that both comes "from the Sun" and is reflected as "rays of light."

> From what I understand, the greenhouse effect is where heat from the Sun enters our atmosphere and reflects off the Earth, but can't get back out. It can't get out because all of the man made pollutants allow heat in, but not back out of the atmosphere. This causes a rise in temperature called global warming. My guess as to why rays of light can get in but not out is they lose energy or get dispersed on entry and reflection off the Earth so it doesn't have the energy to break back out of the atmosphere. (F03P07.093)

Contrast this quote with the descriptions below in which heat is referred to along with gases, moisture, and particles.

> The greenhouse effect occurs because there is a layer of gas which surrounds the Earth and separates us from the vacuum in space. In a sense, this layer protects us from things in space and at the same time keeps gases from escaping Earth into space. The greenhouse effect is when the atmosphere layers holds in heat and gases, making the Earth warm up and then having no way to cool this down. It occurs just like a greenhouse, but instead of glass pains [sic] keeping heat and moisture in, layers upon layers of gas do. (F03P07.128)

> Pollution from humans is causing the Earth atmosphere to change and begin to absorb more of the particles (heat maybe) which used to be reflected away from the Earth. (S04P09.051)

These and related descriptions of heat are more closely aligned with the student conceptual model of heat as a substance.

The above analyses indicate that student models of the greenhouse effect involve trapping of energy and trapping of matter. Table 2.5 below categorizes all 277 surveys that described trapping models based upon student descriptions of what is being trapped.

Table 2.5 Trapping of energy or matter (SSR.vA)

Description of What is Trapped	Number of Students	Percent of Surveys (n=277)
Something is trapped but description is not specific	53	19%
Matter is trapped	61	22%
Energy is trapped	146	53%
Both matter and energy are trapped	17	6%

While models involving trapping of energy (n=146) are over twice as common, models involving trapping of matter are also prevalent (n=61). Finally, 17 students (6%) described that both trapped energy and trapped gases are involved with the greenhouse effect. The following student quote provides an example of this:

> The greenhouse effect is an area of gases that will not let light pass through it. The gases get trapped by the hot air that surrounds it. (F03P06.060)

> I'm not sure but I believe the greenhouse effect has something to do with pollution. When all the pollution gets trapped in our atmosphere it causes an effect like that of a greenhouse where energy can enter the wall or barrier but can't escape. (F03P07.114)

The descriptions and diagrams found throughout this section reveal that students are often unclear on the role Earth's atmosphere as part of the greenhouse effect. Apparently, some students have learned that the greenhouse effect involves something being trapped inside the atmosphere, but they have not yet developed a sophisticated model in which greenhouse gases interact with radiant energy rather than matter.

2.4.2 Trapping through Reflection

Another weakness in student models is the nature of the interaction between energy and the greenhouse gases. In reality, greenhouse gases absorb certain wavelengths of energy and then re-emit this energy at similar wavelengths but in random directions. In terms of the number of students who identified trapping as a mechanism for the greenhouse effect, roughly 8% (n=22) described that energy was absorbed by the atmosphere and only 2% (n=6) correctly explained that this energy was then re-emitted by greenhouse gases. A much more popular explanation for how greenhouse gases trap energy involved reflection and bouncing. At least 21% (n=57) of the students who described trapping models explained that light becomes trapped because it bounces around inside the atmosphere and is reflected by the atmosphere.

> The greenhouse effect is when the heat from the Sun enters the Earth's atmosphere. It is reflected off of the Earth's surface and then bounces back to pass thru the atmosphere. But it is again reflected off of the gases in the atmosphere and it constantly bouncing back and forth from the

> Earth and the atmosphere till all of its energy has been transferred. (F03P07.013)
>
> The greenhouse effect deals with the energy light waves use in Earth's atmosphere. When a light wave enters into the atmosphere, it bounces off the Earth and continues back up to the atmosphere, but it has used a lot of energy to do so, so it doesn't contain enough energy to get out of the atmosphere, so it repeats bouncing between the Earth and its atmosphere. This creates energy or heat, with all of this heat heating the atmosphere it changes the temperatures of the Earth. (F03P06.109)

In the latter quote, the student describes that the energy reflecting back and forth between the surface and atmosphere has somehow used up its energy and is weaker as a result of reflection. This idea of energy getting tired or weaker as it travel through a medium is discussed by Guesne (1985). Student misconceptions regarding the nature and behavior of light affect the mental models that they construct for the greenhouse effect.

2.4.3 Permanent Trapping

Finally, it was noted that very few students explicitly describe that the trapping of energy in Earth's atmosphere is temporary. In reality, the Earth system is in energy balance, with an equal amount of energy leaving the Earth system to space as arrives from space. The greenhouse effect affects the flow of energy "through" the atmosphere and influences the temperature profile within the atmosphere, but it does not decrease the amount of energy leaving the system. However, student descriptions indicate models of "permanent trapping" of in Earth's atmosphere. As described below, students did not have a strong appreciation for energy balance and the fact that just as much energy is radiated from the Earth system as is absorbed. This was revealed in SSR.vA through coding whether students described energy entering from space, leaving to space, or being trapped in the atmosphere. While 221 students (40%) described some form of energy or matter arriving in from space and 277 (50%) explained that energy or matter was somehow trapped by the atmosphere, only 12 (2%) of all students surveyed mentioned that energy or matter ever leaves Earth's atmosphere out to space. The brief sample of student quotes and diagrams below provides examples of student conceptions that light and energy are permanently trapped in the atmosphere:

> From what I understand, the greenhouse effect is where heat from the Sun enters our atmosphere and reflects off the Earth, but can't get back out. It can't get out because all of the man made pollutants allow heat in, but not back out of the atmosphere. This causes a rise in temperature called global warming. My guess as to why rays of light can get in but not out is they lose energy or get dispersed on entry and reflection off the Earth so it doesn't have the energy to break back out of the atmosphere. I would like to know if it is really man made, though. (F03P07.093)

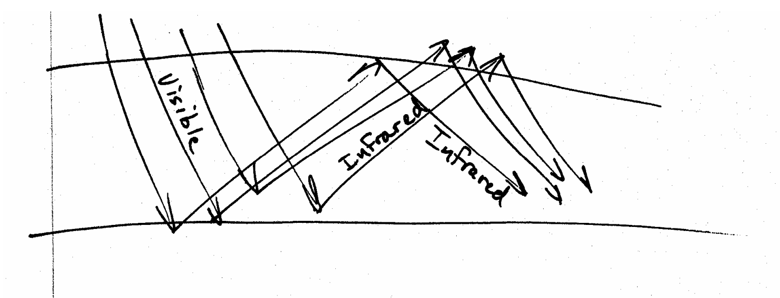
> The greenhouse effect is the warming of the planet. It is causing the Earth to warm up by allowing more energy (light) into the atmosphere than what is escaping. Why aren't the different forms of energy escaping? Because in our atmosphere air pollution from humans is creating the blanket that keeps the light energy "in" our atmosphere. (F03P07.060)

> The greenhouse effect is what happens when the rays of energy that enter the Earth's atmosphere get trapped here. When the rays touch the Earth and get retransmitted they are not as strong and aren't able to get out of the atmosphere again. (F03P07.072)

2.4.4 Additional Insight into Trapping from SSR.vC4

To summarize, while many students describe models for the greenhouse effect in which somehow something is trapped somewhere in the atmosphere, student definitely lack a sophisticated understanding of the details of this "trapping." Gases and matter are often believed to be the important entity that is trapped rather than energy. Student understanding of heat is equally vague. The process by which energy interacts with greenhouse gases most commonly involves reflection rather than absorption and re-emission, and student rarely provide an understanding of energy balance and that energy is still leaving the Earth system even with a greenhouse effect. Even when students possess more sophisticated understandings that the greenhouse effect involves a conversion of energy from visible to infrared light at the surface, they still often lack complete or accurate mental model of the actual greenhouse effect process. The student below correctly describes the conversion of visible light into infrared light, but describes and draws a mental model that appears to involve reflection and does not show energy leaving to space:

Figure 2-6 Student diagram (F03P06.015)



> I think the greenhouse effect occurs because visible light is able to enter the atmosphere and the infrared light that it generates when it strike the Earth's surface is not able to escape the atmosphere. The infrared light is reflected by the atmosphere and returns to the surface. (F03P06.015)

An effort was made to follow up on trapping models during the Spring 2005 administration of Survey SSR.vC4 (see Appendix D). Students were given a drawing of outer space, the atmosphere, and the surface of the Earth and the following prompt:

> The diagram below shows visible light (solid arrow) and infrared light (dashed arrow) from the Sun arriving at the top of Earth's atmosphere. Show what happens to each of these forms of light as they interact with

> the atmosphere and surface. Use SOLID arrows to represent visible light and DASHED arrows to represent infrared light. Provide a brief description of what is going on in your drawing. If other forms of light are involved, describe how you show this in the diagram.

This survey item focused student responses towards a flow diagram of energy through Earth's atmosphere and also provided a standardized template for comparing student drawings. Students were also asked to describe their diagrams.

Out of the 58 pre-instruction student responses, seven categories of responses were identified. Table 2.6 summarizes each of these categories.

Table 2.6 Categories of energy transport diagrams (SSR.vC4)

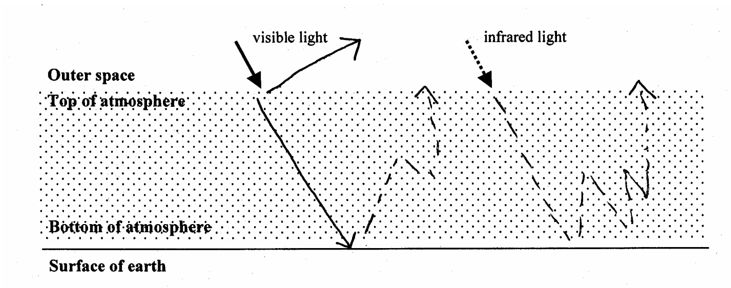
Diagram Category	Number of Students	Percent of Surveys (n=57)
Students who thought visible and infrared both penetrate to surface but interact with atmosphere differently	15	26%
Student who thought only one form of energy penetrates to surface and that they interact differently with atmosphere	14	25%
Students describing greenhouse effect model with infrared light bouncing in atmosphere but escaping to space	8	14%
Students who did not differentiate between visible and infrared light in atmosphere	7	12%
No response / "No clue"	7	12%
Students specifically describing that the ozone layer blocks visible and infrared light differently	4	7%
Ambiguous / difficult to categorize	2	4%

A more detailed description and sample diagrams related to this table follow.

First, 14% (n=8) of the students provided diagrams reminiscent of textbook descriptions of the greenhouse effect. Their explanations involved visible light passing directly through the atmosphere and reflecting straight back to space while infrared light that reflected off the surface was somehow trapped, either permanently or temporarily.

Of these, half (n=4) indicated that infrared energy eventually made it to space, as described by the student explanation of the diagram below:

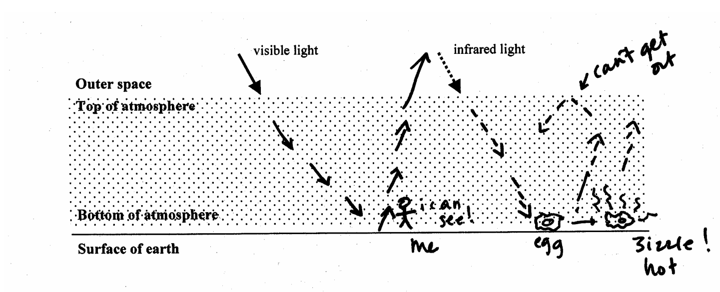
Figure 2-7 Student diagram (3C3-06)



> Some visible light is bouncing right back to space, some absorbed in surface heating atmosphere. I think it releases as infrared moving through atmosphere until it eventually escapes again. The infrared moves about through the atmosphere for a while and then slowly escapes back out. (3C3-06)

Meanwhile, the other half (n=4) depicted that infrared energy does not escape. The student explanation and labeled diagram below shows that infrared light never leaves the atmosphere:

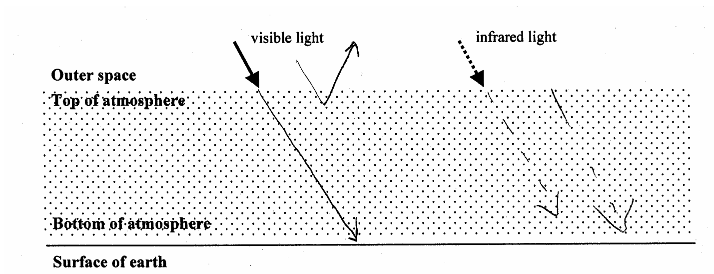
Figure 2-8 Student diagram (3C4-01)



> Visible light enters the atmosphere and lights things up, makes it possible for me to see. It just as easily leaves the atmosphere too. Infrared, however, comes in, brings heat to cook my egg but can't get out again. Think of it this way – the atmosphere is a one-way street when you talk about infrared. What comes in doesn't come out. This because the light entering in wavelength X but when it gets to Earth, it cools and changes to wavelength Y but can't go through the screen of the atmosphere. (6C4-01)

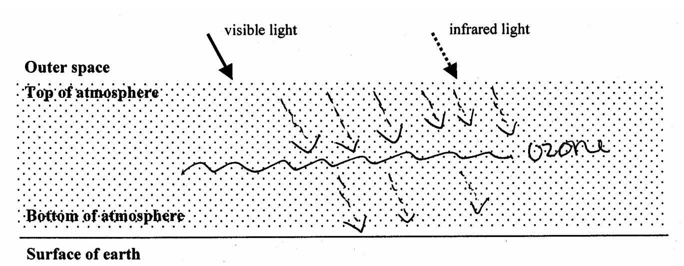
Meanwhile, 7% of the students (n=4) specifically referred to the ozone layer and described that it blocked certain types of energy. Some students described that visible light is blocked by ozone (see Figure 2-9), while others second described infrared light being blocked by ozone (see Figure 2-10):

Figure 2-9 Student diagram (2C4-03)



More infrared light goes through the ozone. (2C4-03)

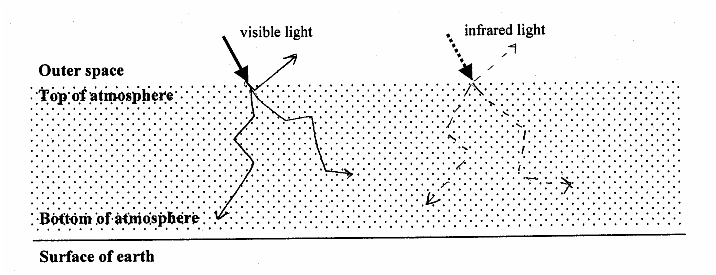
Figure 2-10 Student diagram (3C4-03)



Ozone layer blocks much of the infrared light and holds heat energy. CO_2 is held and makes earth about 15° warmer. (3C4-03)

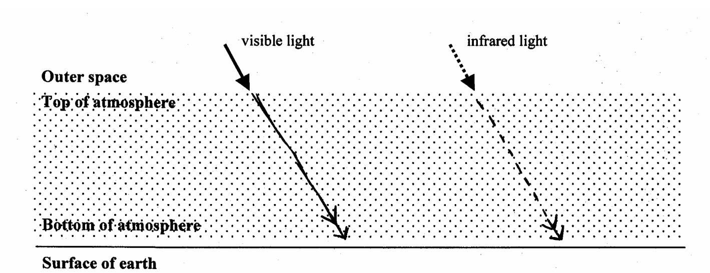
Another category included 7 students (12%) who showed both visible and infrared light interacting with the atmosphere in an identical manner. As the figures below shows, a variety of interaction models were expressed, but these surveys were grouped because the two forms of light behaved identically:

Figure 2-11 Student diagram (6C4-12)



Both visible and infrared light are deflected by atmospheric particles, causing some of the light to be projected back into space, but not all of it. (6C4-12)

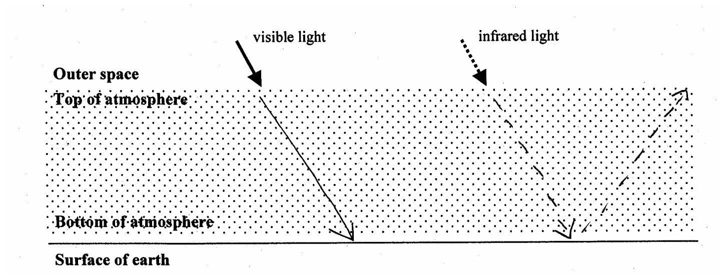
Figure 2-12 Student diagram (5C4-05)



This diagram shows both types of light cutting through the atmosphere and making its way to the surface of Earth. The light cuts through the atmosphere to the Earth and is hurting the atmosphere. (5C4-05)

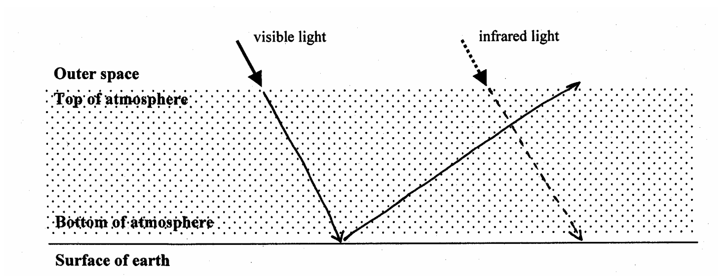
A large category of 15 students (26%) described that both visible and infrared energy penetrated to the surface of the Earth, but that the two forms of energy interacted with the atmosphere differently. In two cases visible light was absorbed by the surface while IR was reflected; in another case, this was reversed:

Figure 2-13 Student diagram (6C4-04)



Visible light is absorbed and infrared light is reflected. (6C4-04)

Figure 2-14 Student diagram (1C4-05)

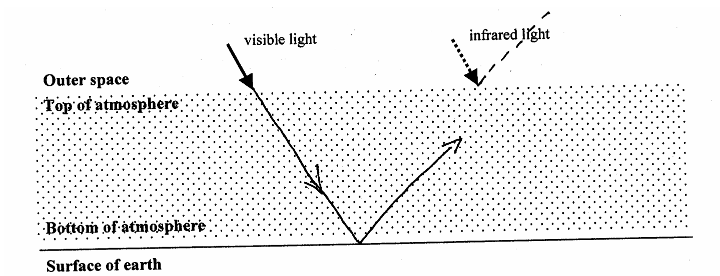


The visible light reflects back towards the top of the atmosphere, and the infrared light simply stays on the Earth's surface. (1C4-05)

In one case, visible was refracted while IR was reflected at the surface. In 4 cases visible light had an easier time penetrating the atmosphere while infrared light was more likely to break up, deteriorate, change, or scatter in the atmosphere; however in three other cases, this was reversed. In two cases, the two forms of energy were swapped, with visible turning into infrared and vice versa. Finally, two cases described that visible and infrared light refracted or bent through the atmosphere differently. These responses describe a variety of interactions between infrared and visible light, although none of them provide an accurate description of the greenhouse effect.

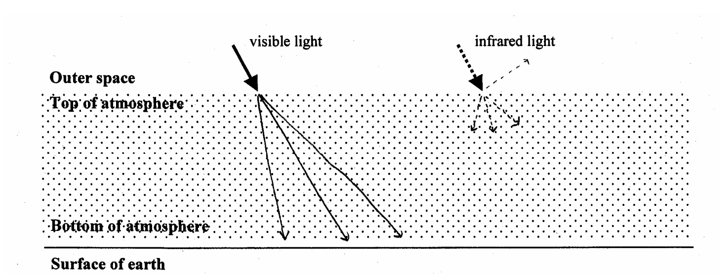
Another category of 14 students (25%) expressed that one form of energy made it through the atmosphere to the surface while the other did not. In 3 of these cases, infrared light never even entered the atmosphere. Rather, it was reflected off the top of the atmosphere to space. In 7 of these cases, infrared light made it into the atmosphere but not to the surface. In 4 cases, infrared light made it to the surface but in a diminished form. Examples of each of these three cases are shown below:

Figure 2-15 Student diagram (6C4-09)



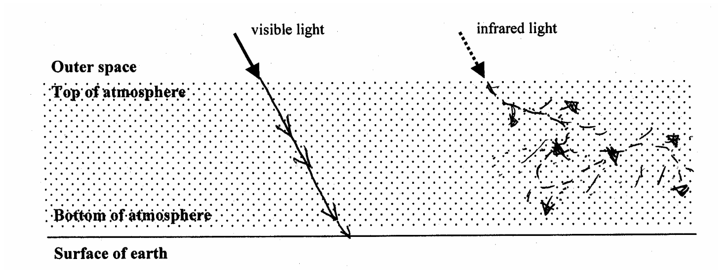
This diagram shows how there are several different kings of light that enter Earth's atmosphere. And with the two that are shown, visible light enters atmosphere, then reflects off Earth's surface. Whereas the second form of light is infrared light where it hits the atmosphere and gets reflected back out to space. (6C4-09)

Figure 2-16 Student diagram (1C4-01)



What I am guessing is that most or all of the visible light will come through the top and only some of the infrared light will come through, but the infrared light that does come through will not be able to leave back through the top. Thus creating the greenhouse effect. (1C4-01)

Figure 2-17 Student diagram (6C4-02)



> Visible light is able to pierce through the Earth's atmosphere and touch the Earth, thereby providing daylight for plants, humans, etc. Infrared light can pierce some of the Earth's atmosphere, but then spreads out and dissolves/dissipates so that only a small portion of it actually gets to Earth's surface. (6C4-02)

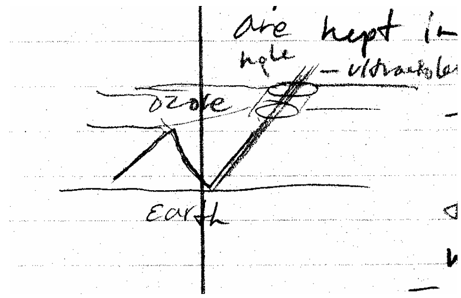
From the above description, it is apparent that there is wide range of ideas about the manners in which visible and infrared light interact with the atmosphere. Encouragingly, 76% of the students surveyed described that visible light interacts differently with the atmosphere than infrared light. However, there was a wide variety of ideas about the nature of each interaction, and only 14% were able to provide diagrams consisting of most of the elements commonly found in a "textbook" diagram.

2.5 Models Involving Both Trapping and Increase in Energy

Coding of Survey SSR.vA also revealed that students combined both of the above models to explain the greenhouse effect. Student described that ozone holes and degradation of the atmosphere let more light into the atmosphere and that this light was then trapped by the atmosphere. Students explained that both of these would lead to increased energy in the atmosphere and higher temperatures.

The student's response below provides a description and a diagram showing ultraviolet light entering through a hole in the ozone layer along with this energy being trapped by the "good ozone layer parts":

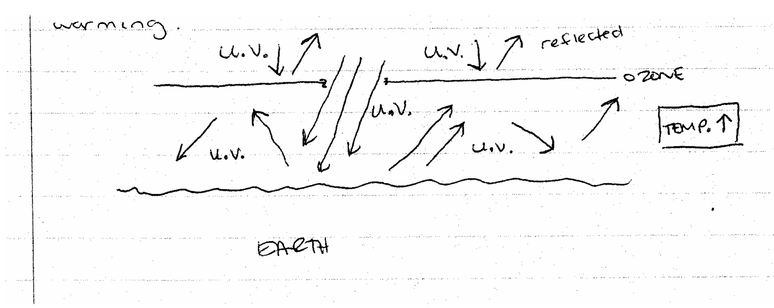
Figure 2-18 Student diagram (F03P07.115)



> The greenhouse effect is caused by damage done to the ozone layer. Ultraviolet rays get through the ozone layer and then try to get out but are kept in by the good ozone layer parts. This eats up the Earth like a greenhouse. This changes the temperature of the Earth by making it hotter. The ozone layer gets destroyed by the gases from power plants and cares. It can't be recreated either. (F03P07.115)

Another student provides a similar diagram with light entering through the ozone hole. The student also specifically refers to energy bouncing and reflecting off of both sides of the ozone layer:

Figure 2-19 Student diagram (F03P07.084)



> The greenhouse effect is the gradual heating of Earth (global warming). There are many factors that contribute to the G.H. effect: carbon dioxide, o-zone, the Sun, the atmosphere, pollution, and more. Basically, as more UV light enters the Earth the Earth begins to heat up. The hole in our

> ozone allows more UV light which as a negative result warms our planet. This UV light bounces around inside our Earth's atmosphere. As the hole expands, more light enters hence more warming. (F03P07.084)

Finally, one student describes both penetration of energy through the ozone hole along with a trapping model in which heat is associated with the substance of pollution:

> The atmosphere acts as a greenhouse, holding in heat and pollution. Because the heat is staying in the Earth's atmosphere, Earth's average temperature is rising and this is slowly melting the polar ice caps. Also there's a huge hole in the ozone over Australia which allows for more of the Sun's rays to penetrate, adding to the heat. (S04P09.096)

Models involving both penetration and trapping of energy from the Sun commonly referred to ozone, the ozone layer, or ozone holes as being involved in the greenhouse effect. As described in Section 2.3, 186 students specifically reference ozone in their descriptions. Table 2.7 shows that 63% of these descriptions focused solely on an increase in the amount of energy entering the atmosphere due to ozone depletion. A smaller percentage (11%) described ozone as a trapping agent alone. However, 17% (n=32) of students combined the two concepts and thought that the ozone layer both allowed more energy to enter and also trapped energy.

Table 2.7 Ozone depletion and trapping models (SSR.vA)

Model	Number of Students	Percent of Surveys Identifying Ozone (n=186)
Ozone depletion and/or increase in energy entering atmosphere	117	63%
Trapping of energy inside atmosphere by ozone	21	11%
Combination of increase in energy and trapping of energy	32	17%
Different model or no specifics	16	9%

Students who were aware of both ozone depletion and the greenhouse effect easily co-opted both of these phenomena in explaining why surface temperatures on Earth are higher. In the absence of information about the relative amounts of radiative forcing associated with ultraviolet energy passing through the ozone layer compared to heating by visible and infrared energy, students were able to adopt both mechanisms as potential heating agents for the Earth.

On Survey SSR.vC2, students were given the following prompt:

> A common quote used by students who were asked to explain the greenhouse effect is that "Pollution is a major cause of the greenhouse effect." What form or forms of pollution do you think these students are referring to and how does the pollution cause the greenhouse effect, if at all?

As shown below, the frequency of responses were similar to those found in Table 2.7. Ozone depletion was described most frequently (40%) followed by trapping of something (31%). However, a larger percentage of students did not provide any mechanism for the greenhouse effect (19%) in answering SSR.vC2, as shown in Table 2.8.

Table 2.8 Ozone depletion and trapping models w/ pollution prompt (SSR.vC2)

Model	Number of Students	Percent of Surveys (n=58)
Ozone depletion alone	23	40%
Trapping alone	18	31%
Neither	11	19%
Both ozone depletion and trapping	6	10%

Interestingly, the number of students who explicitly described trapping of energy (n=8) on SSR.vC2 was equal to those student explicitly describing trapping of gas (n=8).

2.6 Other Models

In addition to the previously discussed models, other explanations for the greenhouse effect were supplied in SSR.vA. While these were provided at much lower frequencies (1-3%), they are described here briefly to provide a sense of the variety of ideas and beliefs associated with the greenhouse effect. Some of these models were used as distracters in the Greenhouse Effect Concept Inventory (GECI).

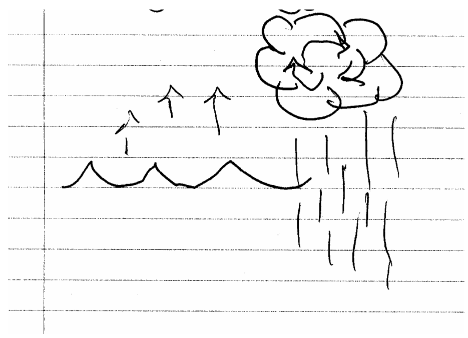
Several students provided descriptions involving circulation and convection of heat in the atmosphere:

> Since warm air rises and we have an atmosphere surrounding the planet, the warm air will rise and sort of become “trapped in the atmosphere. This is what warms the Earth. The heat simply cannot escape the atmosphere. (S04P09.062)

> The greenhouse effect is the layer of gases in the atmosphere caused by human’s pollution. Such pollutants as CFCs, farmland emissions, automotive emissions, etc., are trapped in the atmosphere. These pollutants trap the air circulation and cause the Earth’s temperatures to rise, such as in a greenhouse. (F03P06.041)

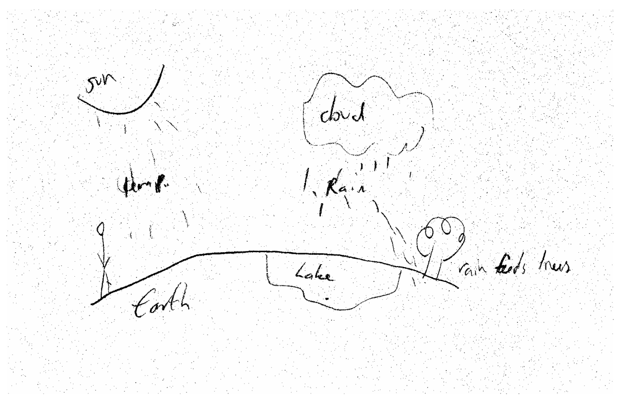
Another theme involved the description of geochemical cycles within the Earth system. One of these was the water cycle, with reference to processes of evaporation, condensation, and precipitation:

Figure 2-20 Student diagram (S04M53.049)



> The greenhouse effect is when the cycle of weather happens and as a result the greenhouse effect happens. Precipitation, condensation, and evaporation occurs on Earth (S04M53.049)

Figure 2-21 Student diagram (F03P07.107)



> The greenhouse effect is the basic make-up of our environment. We are trapped underneath the Earth's atmosphere and everything is circling around it. The rain comes from water from the Earth which evaporates and pours back down. This rain feeds the plants that photosynthesize from the Sun. The Sun puts off a certain amount of energy for this to work. Rivers flow in lakes and oceans. Fish and marine life feed off of the Sun. In other words, it's a huge cycle of the Earth's environment that makes it possible for everything to survive. (F03P07.107)

Students also described the carbon cycle and photosynthesis as an important part of the greenhouse effect:

> The greenhouse effect happens when energy from the Sun combines with the oxygen and carbon dioxide of plants. (F03P07.002)
>
> The greenhouse effect is the effect of the air in the Earth's atmosphere. As the air is used, it is recycled in plants and trees and then put back in the atmosphere. (F03P06.161)

Another description used by students described the Earth's atmosphere as a lens or filter that could magnify, refract, concentrate, or condense energy from the Sun:

> The greenhouse effect is magnification of ultra-violet rays due to certain gases in Earths atmosphere. The light is magnified in the atmosphere allowing more rays to get to the surface. (F03P06.023)
>
> The greenhouse effect is when light entering the Earth's atmosphere is concentrated or intensified which makes the rays stronger and the Earth hotter. Additionally the heat is some how trapped in the atmosphere which does not let the Earth cool down. (F03P07.031)

Finally, students supplied responses that associated the greenhouse effect with Earth's magnetic field, Earth's orbit around the Sun, solar power, and removal of carbon monoxide from the atmosphere. This brief summary of alternative mechanisms for the greenhouse effect is not exhaustive but does shed light on the variety of ideas offered by students. However, it is important to note that the ideas expressed in this section were provided in written responses much less frequently (1-3% of surveys) than the previously discussed ideas of atmospheric trapping and degradation of the atmosphere.

2.7 Analogies for the Greenhouse Effect

Several of the surveys provided analogies for the greenhouse effect. The following analogies listed in Table 2.9 were offered on Survey SSR.vA.

Table 2.9 Greenhouse effect analogies (SSR.vA)

Analogy	Number of Students	Percent of Surveys (n=558)
Plant greenhouse	109	19.5%
Blanket	14	2.5%
Shield	6	1.1%
Wall	3	0.5%
Filter	3	0.5%
Lense	2	0.4%
Oven	1	0.2%
Microwave	1	0.2%
Bubble	1	0.2%
Telescope	1	0.2%
Dome	1	0.2%
Conductor	1	0.2%

Roughly 20% of the students (n=109) used the analogy of a human-built greenhouse for growing plants as part of their explanation of the atmospheric greenhouse effect. Of these, roughly 80% (n=84) did not provide details on how a plant greenhouse works; they described that the greenhouse effect is "like a plant greenhouse" and gave an incomplete or missing description of why a plant greenhouse was warmer. Of the remaining students, 13% (n=14) described the physics of a plant greenhouse as involving light or electromagnetic radiation flowing in and out of the greenhouse, similar to the student below who describes shorter radiation waves penetrating and become trapped:

> The greenhouse effect has to do with waves. It's like how you get into your car and it is scorching inside, but maybe only about 80 degree's outside . . . you forgot to crack your windows, because the shorter radiation waves are able to penetrate the glass windows into the car (like the Earth's atmosphere), but then become trapped inside, so the heat builds up. The radio wavelengths lose their power (become longer and cannot escape/penetrate their way out.) (F03P07.148)

A roughly equal number (10%, n=11) described a plant greenhouse as involving the flow of gases in and out of the greenhouse. This latter group of students described models in which a plant greenhouse traps warm air and does not let it escape out of the greenhouse:

> A greenhouse is used to keep heat and moisture given off by plants in the same area. The 'greenhouse effect" on the Earth is similar in that the idea suggests carbon dioxide gets caught in our atmosphere, becoming the greenhouse. Heat and moisture from the Earth are in turn trapped by the carbon dioxide blanket which causes what many say is global warming or an increase in the average temperature of the planet. (F03P07.019)

These results are similar to the previous discussion of student "trapping models" in which both energy and gases are trapped by the atmosphere in students' minds. An unfortunate weakness of the plant greenhouse analogy is that a plant greenhouse heats up because the convection of hot air is inhibited while the atmospheric greenhouse effect mainly involves radiated energy. Heat flow associated with both types of greenhouse is influenced by both radiative cooling and convective cooling. However, the relative importance of these two processes are opposite for the two types of greenhouses (Nelson et al., 1992). This distinction is not readily apparent to most students, who rarely distinguished correctly between plant greenhouses cooling mostly through convection of air and the atmospheric greenhouse involves mostly radiative cooling. Rather, most student described one or the other process and applied it to both greenhouses. Other analogies provided by more than one student included a blanket, a shield, a wall, a filter, and a lense.

These above results were confirmed more systematically using survey SSR.vC3 with the following prompt:

> Pick one of the following and describe why it is a good analogy for characterizing the behavior of greenhouse gases in the atmosphere. Also, describe any weaknesses with the analogy.

A list of 12 possible analogies was provided and each student was asked to select and describe only one. The analogies identified in SSR.vA were used, although the analogy of "plant greenhouse" was removed based upon its overwhelming popularity shown in Table 2.9. The frequency with which each was selected on SSR.vC3 is shown in Table 2.10.

Table 2.10 Greenhouse effect analogies given following prompts (SSR.vC3)

Analogy	Number of Students	Percent of Surveys with Analogies (n=52)
Blanket	10	19%
Shield	8	15%
Oven	8	15%
Filter	7	13%
Dome	4	8%
Microwave	4	8%
Lense	3	6%
Bubble	3	6%
Sponge	3	6%
Wall	2	4%
Conductor	1	2%
Funnel	0	0%

As this table shows, the most commonly selected analogies was that of a blanket (19%, n=10). This result is consistent with the findings of SSR.vA. Other popular options selected more than 10% of the time were shield, oven, and filter.

2.8 Greenhouse Gases and Sources

A common belief described by students was that the greenhouse effect involves gases and specifically greenhouse gases. 15% of the students (n=86) completing Survey SSR.vA stated that the greenhouse effect was caused by "gases" (n=53) or, more specifically, "greenhouse gases" (n=33) in the atmosphere. Of these, over half (52%, n=45) also offered the chemical name of a specific gas or gases. An additional 128 students similarly suggested the chemical name of a gas, although they did not necessarily state that the chemical was a gas. Assuming these students knew that the chemicals they listed (e.g., carbon dioxide, methane, CFCs) are also gases, the total number of students describing that the greenhouse effect is caused by gases was 212 (38%). Table 2.11 shows the ten most frequently named gases on SSR.vA.

Table 2.11 Specific greenhouse gases (SSR.vA)

Chemical Name	Number of Students	Percent of Surveys (n=558)
carbon dioxide, CO_2	117	21%
water, water vapor, H_2O	35	6%
carbon monoxide, CO	17	3%
chlorofluorocarbons, CFCs	17	3%
oxygen, O_2	17	3%
methane, CH_4	12	2%
ozone, O_3	11	2%
carbon, C	7	1%
nitrogen, N, N_2	5	1%

Far and away, carbon dioxide was the most commonly identified greenhouse gas. Water, the second most commonly cited greenhouse gas, was much more commonly referenced in the Spring 2004 classes (19% and 11% of students in the atmospheric science and astronomy classes, respectively) than in the two Fall 2003 classes (1% and 2% of students in the two astronomy classes). This was perhaps due to the timing of the survey administration in the classes – the Spring 2004 classes were surveyed two weeks later in the semester and the atmospheric science class did include an introduction to greenhouse gases prior to the survey. Other gases that were listed at very low frequencies (<1%) included ammonia, nitrous oxides, freon, and hydrogen.

Because Survey SSR.vA did not specifically ask students to identify greenhouse gases, a follow-up survey was administered during Spring 2005 to more carefully and quantitatively characterize the list of gases that students believe to be greenhouse gases. To avoid possible biasing inherent with multiple-choice items, students completing open-ended survey SSR.vC1 were asked to provide written responses to the following prompt: "List the primary greenhouse gases in Earth's atmosphere." Results from these survey items are provided in Table 2.12 which shows all student responses that were written down by more than 1 student.

Table 2.12 Specific greenhouse gases (SSR.vC1)

Student Responses	Number of Students	Percent of Surveys (n=61)
carbon dioxide, CO2, "carbon nioxide"	45	74%
oxygen, O2, O	23	38%
nitrogen, N	16	26%
carbon monoxide, CO	13	21%
hydrogen, H	9	15%
CFCs, "carcinogenic fluro carbons"	7	11%
methane	4	7%
helium, He	4	7%
water vapor, H2O	4	7%
carbon, C	4	7%
ozone, O3, "atmospheric ozone gases"	4	7%
nitrous dioxide, nitrous oxide, NO2, NO3	4	7%
argon, Ar	3	5%
"air pollution from vehicles," "smoke particles," "burnt oil"	3	5%
"aerosoles," "aresol cans"	2	3%
Sulfur dioxide, sulfur dioxide	2	3%

Again, carbon dioxide is the most commonly referenced gas (74%, n=45). Comparing Table 2.11 with Table 2.12, all of the items gases that were identified through coding of SSR.vA re-emerged through the more focused question of SSR.vC1. Not surprisingly, the frequencies are higher for the latter survey because students were directed to identify specific gases in their answers. Note also that the relative frequencies of response are different between the two datasets. In particular, water vapor, which was the second most common response in the SSR.vA surveys, was reported less frequently on the second survey than the following gases: oxygen, nitrogen, carbon monoxide, hydrogen, and CFCs. Possible factors for this difference include the following: 1) Survey SSR.vA was administered mid-semester while SSR.vC1 was completed within the first two weeks of the semester, 2) students may be more likely to mention water vapor when asked to explain the mechanism of the greenhouse effect than they are when asked simply to list common greenhouse gases.

An additional effort was made with Survey SSR.vC1 to probe further into student understanding of characteristics of greenhouse gases. After being asked to provide a list of the primary greenhouse gases, students were given the following prompt: "Describe the main characteristic of these gases that make them greenhouse gases." Many of the 61 responses were consistent with discussions above regarding student ideas of destruction of the atmosphere and atmospheric trapping. The most commonly referenced characteristic (18%, n=11) was that these gases damage the ozone layer and allow more UV energy to enter the atmosphere. A student who listed "CO_2 and aerosoles" as the primary greenhouse gases explains the following:

> They are released into the atmosphere as waste from cars or plant operations. They are harmful to the ozone layer. When that layer thins, more UV light comes through which create a warming effect on Earth, along with being dangerous (harmful) to humans.

A number of students (15%, n=9) described that these gases were related to plants, photosynthesis, and or the carbon cycle as the main characteristic. One student explained, "Plants let off oxygen that humans need to breathe while humans breathe out CO2 that plants need." Another student listed both carbon dioxide and oxygen as greenhouse gases and explained that "plants go through photosynthesis taking in oxygen and shooting out carbon dioxide."

A third response (15%, n=9) involved the trapping of warmth, heat, and/or energy. One student explained "The main characteristic is that they have a long life so they stay in the atmosphere a long time and trap the heat in." Another described "They are able to hold in the heat that we generate on Earth as well as pull in the heat from the Sun." Note that in this last case the student is describing that the heat generated by humans on Earth is trapped by greenhouse gases. Six students (10%) described that greenhouse gases absorb different wavelengths of energy. One student provided a very accurate description of this: "They prevent the escape of infrared light from the Earth's atmosphere by absorbing the rays and re-emitting them in random directions."

Other characteristics that were mentioned at lower frequencies include that greenhouse gases attract or magnify sunlight, contain oxygen, stay in the atmosphere a long time, are essential for life, are harmful for life, are lighter and less dense than other gases, are denser and thicker than other gases, are good insulators, and are gaseous. One student very clearly described the student belief that greenhouse gases are trapped rather than energy being trapped: "These gases are susceptible to be caught in our atmosphere." All of the above explanations are consistent with those discussed in previous sections regarding student models regarding the mechanism of the greenhouse effect.

2.9 Causes of the Greenhouse Effect

Another student belief about the greenhouse effect that was analyzed involved student opinions about whether the greenhouse effect is a natural phenomenon or a phenomenon caused by human and human activities. This issue was investigated both through open-ended and multiple choice surveys and through student interviews.

An important element to this topic has to do with what students perceive the "greenhouse effect" to be. The scientific community distinguishes between the natural background greenhouse effect and recent anthropogenic enhancement of the greenhouse effect due to human activity. However, within the media and even in scientific circles, this distinction is not always made clear and explicit. Often news reports or scientific discussions use the greenhouse effect to indicate global warming and the human-induced greenhouse effect (Kempton, 1991; Rye et al., 1997; Andersson and Wallin, 2000). This distinction is also weak and unclear among the students involved in this study.

In Survey SSR.vA, students were asked to explain what the greenhouse effect is with no additional prompting. From this dataset, it is possible to quantify the number of students who distinguish between the natural and enhanced greenhouse effect. This was done during the coding process by keeping track of student explanations that attributed the greenhouse effect to human activities and those who attributed it to natural causes. Some students described the greenhouse effect as being caused by both natural and human causes. A total of 236 cases (42%) were coded with one of these option. The breakdown of students ascribing natural causes to the greenhouse effect versus placing responsibility on human activities is summarized in Table 2.13 below.

Table 2.13 Natural and human causes of greenhouse effect (SSR.vA)

Cause of Greenhouse Effect	Number of Students	Percent of Surveys Coded (n=236)
Human causes	169	72%
Natural causes	39	17%
Both natural and human causes	28	12%

This data shows that many more students (72%, n=169) think of the greenhouse effect as being a phenomenon caused by human activity than being a natural phenomenon in the atmosphere (17%, n=39). A fraction of students (12%, n=28) attributed the greenhouse effect to both natural and human causes. In coding the SSR.vA surveys, the types of natural occurrences and human activities that students listed were also tracked. Table 2.14 provides a comprehensive list of all causes ascribed to the greenhouse effect along with the frequency of surveys providing these explanations.

Table 2.14 Activities causing greenhouse effect (SSR.vA)

	Number of Students	Percent of Surveys
HUMAN CAUSES		(n=197)
Pollution	133	67.5%
Chemicals	23	11.7%
Aerosols	22	11.2%
Cars	21	10.7%
Technology, industry	14	7.1%
Deforestation	8	4.1%
Burning Fossil Fuels	5	2.5%
Population Growth	3	1.5%
Refrigerants	3	1.5%
Acid Rain	1	0.5%
Gasoline	1	0.5%
Light Pollution	1	0.5%
NATURAL CAUSES		(n=67)
Plants	24	35.8%
Animals	11	16.4%
Clouds	11	16.4%
Photosynthesis	10	14.9%
Humidity	5	7.5%
Volcanoes	1	1.5%
Magnetic Fields	1	1.5%
Orbital Position	1	1.5%
La Nina	1	1.5%

Some surveys provided multiple causes while others did not describe a cause or were not specific about whether the greenhouse effect was caused by natural or human sources. Regarding human sources, the most popular description was that the greenhouse effect is caused by pollution. Chemicals, aerosols, cars, technology, and industry were also commonly listed as leading to the greenhouse effect. Plants (along with photosynthesis), animals, and clouds (along with moisture and humidity) were described most commonly as natural causes for the greenhouse effect.

Additional insight can be gained by looking at whether students described the greenhouse effect as being harmful, beneficial, or benign for the environment. Student opinions on this subject depend, of course, on what their conception of the greenhouse effect is – whether it is a trapping of energy that keeps planetary surface temperatures above freezing, a destruction of the ozone layer that leads to increases in skin cancer, etc. While attempts have not been made to correlate student mechanisms for the greenhouse effect with their attitudes towards its usefulness or danger on Earth, general student impressions about the term "greenhouse effect" were identified. Roughly 10% of the 558 surveys provided opinions about the greenhouse effect (n=56). Of these, 39 (66%) described the greenhouse effect as being harmful or damaging to Earth and humans. A smaller number of students (21%, n=12) thought that the greenhouse effect was beneficial for life. Finally, 5 students (9%) thought the greenhouse effect neither hurt nor helped Earth and 2 (4%) thought that it was both beneficial and harmful.

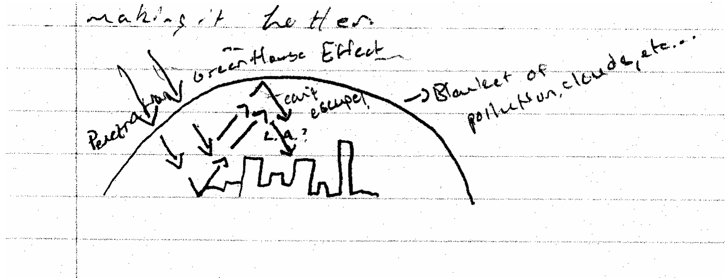
One of the most common causes cited for the greenhouse effect was "pollution." However, it was unclear from many surveys what students meant by this term. In some cases, students were specifically describing air pollution in the form of smog, smoke, and particulates:

> The greenhouse effect . . . I know of it w/ respect to pollution. More pollution causes smog and whatnot to surround the Earth's atmosphere. Heat, energy is held in by the pollution, thus increasing temps on Earth. My dad has a greenhouse. Sometimes its hard to breath in there cause of the moisture. It's real hot too. Damn that pollution. But why doesn't the pollution just float off into space? I guess gravity keeps it here. Which is good cause aliens don't want our ****. (F03P07.012)

In other cases, students appeared to be using the term as a more general term for the many gases found in car exhaust – including CO_2 and particulates. In some cases, the students appeared to be describing a general term that could be regarded as waste products of society. These answers are consistent with findings in the literature (e.g., Boyes and Stanisstreet, 1992; Francis et al., 1993; e.g., Bostrom et al., 1994) that students typically associate the greenhouse effect with other environmental issues including ozone depletion and pollution.

In some cases, students described the greenhouse effect as being a more localized than global. Typically, these answers involved descriptions of domes, shields, or blankets covering localized areas and trapping either heat or particles inside. A representative student drawing and explanation is provided below:

Figure 2-22 Student diagram (F03P07.026)



> I believe that the greenhouse effect is an invisible blanket in some cities though more apparent, like Los Angeles. This blanket allows light to penetrate, but once the light bounces off of the surface and goes to leave the atmosphere, it just goes back up, hits the blanket and sends it back down to Earth trapping the waves of light, making it hotter. (F03P07.026)

In survey SSR.vC2, a specific question was asked to get a better handle on the form of pollution students might have been describing (see Appendix D). Students were asked to answer the following question:

> A common quote used by students who were asked to explain the greenhouse effect is that "Pollution is a major cause of the greenhouse effect." What form or forms of pollution do you think these students are referring to and how does the pollution cause the greenhouse effect, if at all?

Out of the 58 students surveyed, the majority (52%, n=30) identified human activities involving transportation (e.g., cars, motorcycles, automobiles) as the main source of pollution related to the greenhouse effect. Other popular answers included descriptions of industry (power plants and factories), fossil fuels (coal, oil, refineries), and aerosols (aerosol cans, hairspray) as primary sources of greenhouse gas pollution (see Table 2.15).

Table 2.15 Sources of pollution causing greenhouse effect (SSR.vC2)

Source	Number of Students	Percent of Surveys (n=58)
Transportation (cars, automobiles, motorcycles)	30	52%
Industry (power plants, factories)	21	36%
Fossil fuels (coal, oil, refineries, burning fossil fuels)	15	26%
Aerosols (aerosol cans, hairspray)	9	16%
Human products (plastics, artificial products)	3	5%
Natural sources (volcanoes)	2	3%
Plants	2	3%
Hazardous waste	2	3%
Burning forests	1	2%
Smoking	1	2%

As shown earlier in Table 2.8, damage to the ozone layer followed by trapping of energy and gases was identified as the primary manner in which the pollution from the above sources cause the greenhouse effect. Students responding to this survey item also frequently reference specific gases, including carbon dioxide (21%, n=12), carbon monoxide (19%, n=11), CFCs (10%, n=6), automobile exhaust (10%, n=6), and smog (9%, n=5).

Additional insight was gained into student connections between pollution and greenhouse gases on Survey SSR.vC1. In addition to being asked to list and describe the main characteristics of greenhouse gases (see Section 2.8), students were also asked the following prompt: "When you look towards the sky, which of the above substances, if any, could you see with your naked eye? Justify your response." Four primary categories of responses emerged from this prompt. The first group, which included 22 students (36%), was that greenhouse gases are invisible. Students often clarified that "gases are usually invisible" and assumed that greenhouse gases were invisible. The second category (30% n=18) involved students who thought that greenhouse gases were visible. Common references were made in this group to smog, pollution from power plants, and clouds or water vapor:

> We can see pollution → mostly from our cars, it forms in a smog-like layer. So I guess we can see carbon monoxide and dioxide.
>
> You can see CO2 - it is released from cars, so if traffic is really bad in the city, you can see the smog sometimes.

The third category (13%, n=8) involved students who for the most part described that greenhouse gases are invisible, but they also mentioned or described that you could sometimes see smog over cities that might was also associated with greenhouse gases. This group sits on the fence between the first two groups, explaining that greenhouse gases are visible if there are a lot of them, which is more common in polluted areas. As one student explained, “You cannot see these substances unless they take on the form of smog. In general these gases are colorless.” Another described that the gases could be illuminated by cities: “They are fairly invisible unless there is a high concentration like above a city, then you can see it as smog.” Finally, the remaining 13 students either provided no answer (7%, n=4) or provided answers related to extraneous phenomena such as why the sky is blue, why Sunsets are red, rainbows, and red shifts (15%, n=9). Table 2.16 below re-summarizes the number of students falling into each of the above categories.

Table 2.16 Visibility of greenhouse gases (SSR.vC1)

	Number of Students	Percent of Surveys (n=61)
Invisible	22	36%
Visible	18	30%
Invisible except in polluted areas	8	13%
Extraneous (blue sky, Sunsets, rainbows)	9	15%
Blank / no answer	4	7%

As this table shows, roughly equal numbers of students described greenhouse gases as being invisible or visible. Of the 18 students who described that greenhouse gases are visible, 89% (n=16) gave explanations involving pollution, smoke, and smog. Including the 8 students who thought greenhouse gases were invisible unless they were in high concentration, many students associate greenhouse gases with visible pollution given off by human activities.

2.10 Consequences of the Greenhouse Effect

SSR.vA surveys often described consequences of the greenhouse effect. These were coded into the following categories: effects on 1) the atmosphere, 2) the oceans, 3) continents, 4) humans, and 5) other living organisms. Table 2.17 shows the breakdown of the number of surveys describing each of these.

Table 2.17 Consequences of greenhouse effect on Earth system (SSR.vA)

Category	Number of Students	Percent of Surveys (n=558)
Atmosphere	344	62%
Life	77	14%
Oceans	40	7%
Humans	22	4%
Land	14	3%

The majority of students (62%, n=314) described the greenhouse effect as something that affects Earth's atmosphere. Table 2.18 provides a breakdown of the specific effects that students described in their written responses. As the table shows, 89% of the 344 students who mentioned atmospheric effects described that the greenhouse effect increases air temperatures at the surface. All of the other atmospheric effects are listed at frequencies below 5%.

Table 2.18 Consequences of greenhouse effect (SSR.vA)

	Number of Students	Percent of Surveys
ATMOSPHERE		(n=344)
Increases atmospheric temperature	294	85.5%
Affects weather	17	4.9%
Affects climate	16	4.7%
Makes atmosphere thicker	10	2.9%
Stabilizes atmospheric temperature	10	2.9%
Makes atmosphere thinner	7	2.0%
Increases humidity	5	1.5%
Decreases amount of oxygen	2	0.6%
Decreases atmospheric temperature	1	0.3%
Causes acid rain	1	0.3%
Removes carbon monoxide	1	0.3%
LIFE (NON-HUMAN)		(n=77)
Increases number of plants and productivity	33	42.9%
Necessary for life	18	23.4%
Causes animal populations to drop	9	11.7%
Decreases amount of plants	9	11.7%
Damages environment	5	6.5%
Causes things to burn	2	2.6%
Decreases biodiversity	1	1.3%
Causes animal populations to grow	1	1.3%
Causes corral bleaching	1	1.3%
OCEANS		(n=40)
Melts polar ice caps	36	90.0%
Causes increase in sea level	10	25.0%
Increases ocean temperatures	4	10.0%
Causes corral bleaching	1	2.5%
HUMANS		(n=22)
Affects human health	14	63.6%
Leads to cancer	9	40.9%
LAND		(n=14)
Causes flooding on land	5	35.7%
Causes things to burn	2	14.3%
Causes drought	1	7.1%
Acid rain damages surface	1	7.1%

Many students who mentioned effects on non-human life described that the greenhouse effect increases the number of plants and how productive those plants are. Students expressed that the greenhouse effect makes plants healthier and allows more plants to grow (n=33). Some students (n=18) also described that the greenhouse effect is necessary for life as we know it on the planet.

With regards to influences on the ocean, students described that the greenhouse effect has or will cause polar ice caps to melt (n=36) and lead to increases in sea level (n=10). Other effects of the greenhouse effect are that it causes skin cancer (n=9) and sickness (n=14) among humans and that it can cause flooding on land (n=5).

Based upon the breadth of investigations into the causes and effects of the greenhouse effect and global warming described in the literature (see Chapter 1), it was decided that the study described here would focus more on the microphysics of energy transfer and the physical processes relevant to the greenhouse effect. In light of this, Survey SSR.vA was not coded comprehensively with regards to student ideas about the effects of the greenhouse effect.

2.11 Ozone Depletion, Global Warming, and the Greenhouse Effect

As has become apparent throughout the preceding sections of this chapter, coding of the SSR.vA surveys revealed that students drew weak distinctions between the following phenomena: greenhouse effect, global warming, ozone depletion, and air pollution. Indeed, students often introduced the terms ozone depletion and global warming in their descriptions without prompting. Students often described the greenhouse effect as being the same phenomenon as global warming or ozone depletion.

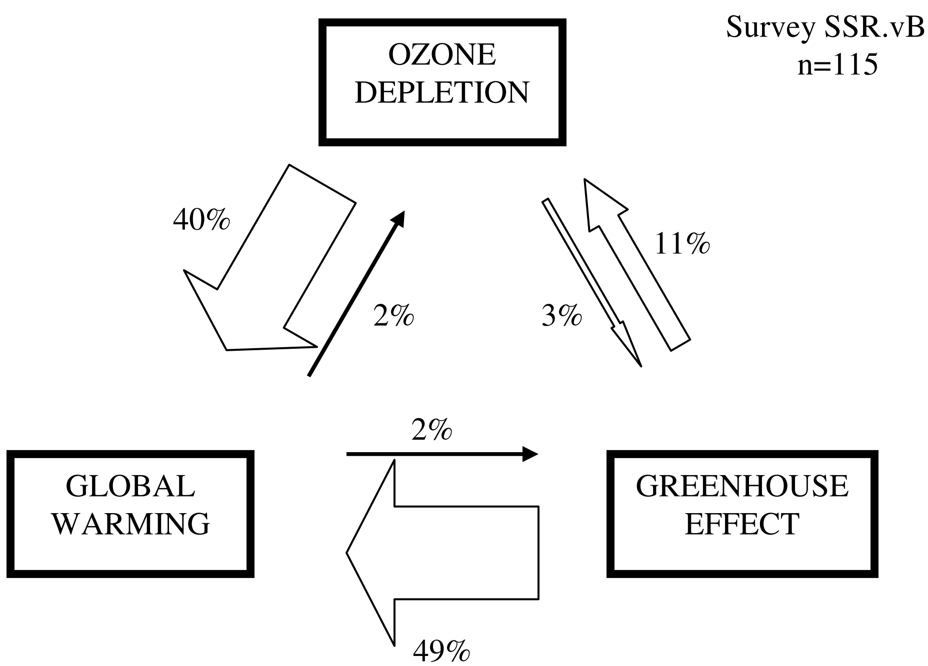
Alternatively, students sometimes indicated that one of these causes or leads to a second (e.g., that the greenhouse effect leads to global warming). Often the greenhouse effect is associated with a number of negative atmospheric environmental issues, including air pollution and ozone depletion. Below is just a brief selection of student responses that reflect this mixing of environmental issues:

> The greenhouse effect is the result of global warming. Because of pollution and other man made causes, holes have developed in the ozone layer of the Earth's atmosphere. These holes are allowing bad/harmful rays into the Earth's atmosphere. The greenhouse effect is when those harmful rays get trapped in our atmosphere. (F03P06.118)
>
> I may be completely off on this response, however I think that it has to do with pollution and global warming. I know that it definitely has to do with the way our planet is affected by light. So this is my guess. I think that the greenhouse effect is how Earth is affected by receiving increasingly strong amounts of light as our ozone layer is becoming depleted. The light is being transformed into heat and the heat becomes more intense as it goes through less ozone and more pollution. (F03P06.126)
>
> I am not quite sure what the greenhouse effect is. My best theory would be that the climate of the Earth is gradually getting warmer due to an increase in air pollution. The air pollution weakens the ozone layer which allows more UV rays to enter our atmosphere. This in turn warms our oceans above normal temperature. Since the ocean is our main source for weather and climate, the world's climate is also affected and becomes warmer. (S04M53.056)

This insight is consistent with previous research on student understanding of the greenhouse effect (e.g., Boyes and Stanisstreet, 1992; Francis et al., 1993; Bostrom et al., 1994). An attempt was made during Spring 2004 to more carefully catalog student distinctions between the greenhouse effect, ozone depletion, and global warming. As described in Section 2.2.2, students from a planetary science class completed Survey SSR.vB. This survey was similar to SSR.vA but prompted students to specifically clarify any distinctions they drew between the three phenomena (see Appendix C). The 115 survey forms were coded by reading through each form and identifying both the models that the student used to describe each of these phenomena and also an indication of whether the students thought these phenomena were the same or causally related.

Figure 2-23 provides the number and percentage of students who indicated that the phenomenon at the tail of the arrow leads to the phenomenon at the head of the arrow. The size of each arrow is in proportion to the percentage of students.

Figure 2-23 Student connections between GHE, GW, and ozone depletion



As the figure shows, students most frequently described that the greenhouse effect leads to global warming (49%, n=56) or that ozone depletion leads to global warming (40%, n=46). Of these, 25 students (22%) described that both ozone depletion and the greenhouse effect lead to global warming. Some students described that the greenhouse effect leads to ozone depletion (n=13, 11%), and of these, seven went on to also describe that ozone depletion leads to global warming. The remaining relationships in the figure were reported 3% of the time or less. Not shown in the figure, 12 students (10%) described that the greenhouse effect and global warming are the same thing, and 7 students (6%) described that the greenhouse effect and ozone depletion are the same thing. Also, descriptions from 26 students (23%) did not indicate any relationships between the three phenomena.

Thus, when provided with the terms greenhouse effect, global warming, and ozone depletion, students tend to associate global warming as an effect of ozone depletion and the greenhouse effect more frequently than as a cause of these phenomena. Explicitly naming the three phenomena provides vocabulary for students to distinguish between the different phenomena. When students are asked simply about the greenhouse effect, students described the greenhouse effect, ozone depletion, and global warming but were less specific in distinguishing between these phenomena.

2.12 Summary of Insights from SSR Surveys

To summarize, student-supplied response surveys provided the opportunity to compile a set of frequently held student beliefs and ideas regarding the greenhouse effect. For Survey SSR.vA, students were not biased in their responses by any prompts, clues, or suggestions offered by the survey instrument. The approach also provided an opportunity to gather student language and gauge student understanding independent of the expectations of the researchers and educators involved.

As shown, Survey SSR.vA served as a foundation for the development of more focused student-supplied response survey efforts. The five follow-up SSR surveys focused on greenhouse gases, pollution associated with the greenhouse effect, greenhouse analogies, trapping models, and distinctions between ozone depletion, global warming, and the greenhouse effect. These efforts provided more specific and quantifiable information regarding each of these subtopics while still allowing students to provide language and thoughts with minimal biasing from the survey prompts. There are some shortcomings to the SSR survey approach, however. This method did not allow the opportunity for follow-up questions on unclear points expressed in student responses. Also, the coding process required to derive strongly defendable quantitative results from the qualitative dataset was time consuming and somewhat subjective. For these reasons, themes emerging from the SSR surveys were triangulated through use of multiple-choice surveys and student interviews discussed in Chapter 3.

Central student beliefs regarding the greenhouse effect from this qualitative study are summarized in Table 2.2 at the beginning of the chapter. Out of the 558 students completing Survey SSR.vA, the most common student models for understanding the greenhouse effect involve the following:

- Trapping in Earth's atmosphere (50%, n=277)
    - Trapping of heat (n=101)
    - Trapping of energy: heat as energy, energy, light, sunlight, specific forms of light (n=146)
    - Trapping of matter: heat as substance, gases, gas molecules, pollution, moisture, clouds (n=61)
    - Trapping of both energy and matter (n=17)

- Increase in amount of energy entering as a result of deterioration, thinning, or formation of holes in the atmosphere or ozone (21%, n=117)
- Combination of the above (6%, n=32)

Student trapping models favor bouncing and reflection of energy (mentioned by 21%, n=57) over absorption (8%, n=22) and re-emission (2%, n=6). Additionally, students discussed the release of energy or substances to outer space (2%, n=12) much less frequently that incoming (40%, n=221) and trapped energy and substances (50%, n=277). This result implies that students do not have a strong understanding of energy balance and models of trapping more closely aligned with permanent rather than temporary trapping. The most commonly reported greenhouse gas was carbon dioxide. This was mentioned by 21% (n=117) of student on Survey SSR.vA and 74% (n=45) of students on Survey SSR.vC1 which specifically asked students to list greenhouse gases. The most common source of greenhouse gases describe on Survey SSR.vA was pollution (24%, n=133). The majority of students believe that the greenhouse effect is associated with warming the planet (86%, n=294). Finally, students often associate the greenhouse effect with other atmospheric environmental issues, in particular ozone depletion, global warming, and pollution. Results from Survey SSR.vB indicate that students believe global warming is a consequence of the greenhouse effect and ozone depletion rather than a cause of these (see Figure 2-23).

CHAPTER 3: DEVELOPMENT OF THE GREENHOUSE EFFECT CONCEPT INVENTORY (GECI)

3.1 Concept Inventories

As described in Chapter 2, several central ideas and beliefs held by students regarding the greenhouse effect were uncovered through analysis and coding of 901 pre-instruction Student-Supplied Response (SSR) surveys. Several Multiple-Choice (MC) and Multiple-Choice with Explanation of Reasoning (MCER) items were developed and used to confirm and provide more rigorous quantitative data regarding these ideas and beliefs. Testing of these items over the course of three semesters has led to the final version of the Greenhouse Effect Concept Inventory (GECI) provided in Appendix O. This chapter discusses the development of the GECI and insights regarding student ideas and beliefs that were gained over the course of the development process.

The objectives of this chapter are 1) to provide details regarding the creation and development of GECI survey items, 2) to share insights into student understanding based upon results from the administration of the GECI Survey and student interviews. Presented in thematic sections similar to those in Chapter 2, the chapter shows the evolution of individual survey items. Validation of the GECI survey instrument along with a preliminary control-intervention study is presented in Chapter 4.

An overview of the administration of the GECI is provided in Table 3.1. This table lists the format of each survey version, the semester that it was administered, the number of classes that participated, and the number of students surveyed pre- and post-instruction. Copies of each of the GECI survey instruments are provided in Appendices E, G, L, and N.

Table 3.1 Summary of GECI survey instruments

Survey Label	Description	Semester Administered	Number of Classes	Number of Surveys Collected	
				Pre	Post
GECI.vA1	10 MC questions Multiple choice questions only	Spring 2005	6	57	43
GECI.vA2	11 MC questions Multiple choice questions only	Spring 2005	6	62	46
GECI.vA1A	5 MC from GECI.vA1 5 SSR prompts to explain reasoning	Spring 2005	6	61	41
GECI.vA1B	5 MC from GECI.vA1 5 SSR prompts to explain reasoning	Spring 2005	6	60	40
GECI.vA2A	5 MC from GECI.vA2 5 SSR prompts to explain reasoning	Spring 2005	6	61	41
GECI.vA2B	6 MC from GECI.vA2 6 SSR prompts to explain reasoning	Spring 2005	6	56	42
GECI.vB1	14 MC questions	Fall 2005	17	934	608
GECI.vB2	14 MC questions	Fall 2005	17	845	587
GECI.vC	20 MC questions	Spring 2006	6	577	415
TOTAL			29	2713	1863

3.1.1 Greenhouse Effect Concept Inventory, Version A (GECI.vA)

The preliminary version of the Greenhouse Effect Concept Inventory, GECI.vA, was administered during Spring 2005 to six introductory science classes for non-science majors. Two of these were planetary science classes, two were atmospheric science classes, one was an astronomy class, and the final was a biology class. This last class was intended as a pseudo-control group that did not treat the concept of the greenhouse effect directly as part of the course curriculum.

Twenty multiple choice items were created based upon qualitative data from Surveys SSR.vA and SSR.vB described in Chapter 2. These items were then divided into six different survey versions shown in Table 3.1. Two of these, GECI.vA1 and GECI.vA2, consisted of 10 and 11 multiple-choice content items, respectively. The remaining four versions were Multiple-Choice with Explanation of Reasoning (MCER) surveys. These involved smaller subsets of the 21 multiple choice questions along with prompts asking students to explain their reasoning for each of their answers to the multiple choice items. Surveys GECI.vA1A and GECI.vA1B listed the first five and last five questions, respectively, of Survey GECI.vA1. Surveys GECI.vA2A and GECI.vA2B listed the first five and last six questions, respectively, of Survey GECI.vA2. See Appendix E for more details.

Roughly equal numbers of each of these six survey versions were distributed, with each student completing just one survey version. Students were asked to provide their names on surveys so that pre- and post-instructional surveys could be matched. However, because there was no efficient way to ensure that students took the same version of the survey post-instruction, attempts to create pre-post instructional matches of the GECI.vA surveys were not pursued during data analyses.

Quantitative and qualitative results were acquired from the GECI.vA surveys. Both multiple choice selections and written explanations of reasoning were transcribed to an Excel spreadsheet. Only surveys that were completely blank were removed from the dataset. This data was analyzed using SPSS to generate reports of both pre- and post-instruction response frequency and student explanations for responses. For all response frequency graphs provided throughout this chapter, data from the biology pseudo-control group has been excluded to provide stronger contrast between pre- and post-instruction shifts resulting from instruction.

3.1.2 Greenhouse Effect Concept Inventory, Version B (GECI.vB)

Analyses of data from Survey GECI.vA surveys were used to create Survey GECI.vB, which was administered during Fall 2005. Two similar versions the survey were created (GECI.vB1 and GECI.vB2), each consisting of 14 multiple-choice items related to or expanding upon previously discussed student ideas and beliefs. Each survey addressed similar concepts but with slightly different wording and approaches to assessing student understanding. Several of the items were repeated from Survey GECI.vA. Appendix G provides a copy of the survey items.

The survey was administered to 17 introductory science classes. 934 and 608 students completed Survey GECI.B1 pre- and post-instruction; 845 and 587 students completed Survey GECI.B2 pre- and post-instruction. This represented the largest number of surveys collected for any of the instruments in this study. Student responses were collected using SCANTRON forms. Students were instructed to complete Survey GECI.vB1 if their date of birth was an odd number and GECI.vB2 if their date of birth was an even number. Since student birthdates are presumably static, this should have ensured that students completed the same version of the survey both pre- and post-instruction. Students also provided the last three letters of their middle name and the day and month of their birth as a way of matching student survey forms pre- and post-instruction.

Table 3.2 provides a summary of the type of courses that participated in GECI.vB. Ten classes were Tier 1 NATS courses (see Section 2.1) that specifically addressed the greenhouse effect as part of the curriculum. Four of these classes were in atmospheric science, two in planetary science, two in global climate, one in astronomy, and one in environmental science. A Tier 1 NATS biology class was also recruited as a pseudo-control group that did not specifically cover the greenhouse effect. Of the three Tier 2 classes involved, two were in planetary science and one was in astronomy. Finally, three introductory chemistry courses for science majors were surveyed. Two of these were control groups and the third discussed the greenhouse effect and global warming for one day of the semester.

Data from this survey instrument was cleaned and analyzed using SPSS. Survey forms that were missing 2 or more content items were removed on the basis that students may have had difficulty completing the survey in the time allotted. For survey items with only two response option, surveys in which the student selected a non-viable option were removed. This strategy, along with removing survey forms with patterned bubbling, was removed on the suspicion that these students may not have made a serious attempt at the survey. As Table 3.2 shows, this cleaning process resulted in 869 and 549 pre- and post-instruction GECI.vB1 forms and 772 and 546 GECI.vB2 forms.

Table 3.2 Cleaned cases for GECI.vB by group

Class Description	Number of Classes	Survey Version	Number of Surveys Collected	
			Pre	Post
Tier 1 NATS Intervention	10	GECI.vB1	534	334
		GECI.vB2	477	346
Tier 2 NATS Intervention	3	GECI.vB1	132	85
		GECI.vB2	92	68
Intro Chem Intervention	1	GECI.vB1	98	74
		GECI.vB2	87	73
Tier 1 NATS Control	1	GECI.vB1	46	26
		GECI.vB2	59	29
Intro Chem Control	2	GECI.vB1	59	30
		GECI.vB2	57	30
Total	17	GECI.vB1	869	549
		GECI.vB2	772	546

Response frequency distributions were created for pre- and post-instructional surveys and utilized in the creation of GECI.vC. For all response frequency graphs provided in this chapter, the pseudo-control NATS and all chemistry groups have been excluded. The former was removed to increase contrast between pre- and post-instructional shifts. For consistency with the other GECI datasets, the chemistry groups were removed because they sampled science majors rather than non-science majors.

Because the survey format did not allow students to explain the reasoning behind their selections, a subset of 9 students who completed the pre-instructional survey were interviewed outside of class for ~45 minutes regarding their responses to the questions on the survey version that each completed. See Section 3.2 below and Appendix J for details on the interview protocol. Appendix K provides a summary of the transcript for each interview. This data provided a qualitative reference to validate the manner in which students were interpreting and answering the multiple-choice items on the survey.

3.1.3 Greenhouse Effect Concept Inventory, Version C (GECI.vC)

The third version of the Greenhouse Effect Concept Inventory (GECI.vC) was administered during the Spring 2006 semester. This survey consisted of 20 multiple-choice content items based upon items from the previous multiple-choice survey instruments with slight modifications. There was only one version of Survey GECI.vC. The survey was administered to six sections of introductory science courses (2 astronomy, 2 atmospheric science, and 2 planetary science) both pre- and post-instruction 577 and 415 students, respectively). Similar to Survey GECI.vB, student responses to the survey items were recorded using SCANTRON forms and analyzed using SPSS. Using the same criteria for data cleaning as described above resulted in 556 pre- and 400 post-instruction survey forms. Because each covered the greenhouse effect, all six groups were used to calculate pre- and post-instruction response frequency graphs.

Two of the groups above were sections of the same astronomy course taught by a single instructor. Two were sections of the same atmospheric science course taught by a single instructor. The final two were different planetary science courses taught by different instructors. The paired classes with the same instructor were involved in a control-treatment study described in more detail in Chapter 4.

3.2 Summary of Student Interviews

During Fall 2005, nine student interviews were conducted as part of the development and validation of Survey GECI.vB. Interviews were conducted to confirm whether students were interpreting the wording of the survey items in manners consistent with the intentions of the survey developers. The interviews also provided further insight into student beliefs and reasoning difficulties discussed in previous chapters. All interviewees were students from the same section of a planetary science classes that was surveyed during August 2005. Each of the interviews, which were conducted between September 26 and September 30, was roughly 30-45 minutes long. Six of these students were freshman, one was a sophomore, and two were juniors. Five of the students were male and four were female. All interviews were recorded on audio-tape and later transcribed. Appendix D provides both details regarding the interview protocol and summaries of the interview transcripts. Interested readers are encouraged to review these transcript summaries.

Because there were two versions of the survey, four of the students had completed GECI.vB1 and five students had completed GECI.vB2. For each interview, students were first asked to describe the greenhouse effect in their own words and encouraged to draw pictures if this would help. Next, the interview involved going through the 14 content items from the survey version that the student had completed in August. For each question, the student was asked to provide the best answer along with an explanation of their reasoning. For some of these, the student was asked if there was a second best answer or if there were any answers that seemed particularly wrong. At the conclusion of each interview, the student was asked to re-describe the greenhouse effect and then asked to clarify the distinction between the greenhouse effect, global warming, and ozone depletion.

Items from Survey GECI.vB1 were discussed during interviews with Paul, George, Raoul, and Elizabeth. Items from Survey GECI.vB2 were discussed during interviews with Melissa, Rebecca, Kevin, Conan, and Farah. These names are pseudonyms provided by each of the participants. For most of the survey items, interview data confirmed that students interpreted the items in the manner intended by the developers. However, slight modifications were made to some items and four were removed (GECI.vB Items 6, 24, 25, and 26) based upon the interview data. Interview insights into the development of each survey item are provided throughout the remainder of this chapter.

In addition, student interviews provide an opportunity to engage more interactively with and pursue more deeply student mental models and reasoning processes. The remainder of this section briefly describes some interview samples that are particularly illuminating into the nature of student misconceptions the educational theory of constructivism.

Before turning to individual survey items, it is beneficial to first provide a brief overview of student descriptions of the greenhouse effect. It is also interesting to note that several interesting transitions in student's greenhouse effect models occurred over the course of the half-hour interviews.

Three of the nine students, Rebecca, Kevin, and Elizabeth, provided initial descriptions of increased sunlight passing through the atmosphere as their model for the greenhouse effect. The following quote from Rebecca reflect this model:

> [The greenhouse effect] has something to do with the pollutants and everything that we, as humans, produce are eating up the ozone layer that

> pretty much surrounds the Earth. I don't know exactly what it does, but the problem with that is that the harmful rays from the sun, UV rays, etc., are getting in easier because there's not that protective layer around, and, and I'm assuming that would make us hotter, and, yeah, that's about it.

Kevin's description is similar, although he was less solid in his description. He first describes that carbon dioxide fumes eat the ozone layer and that CFCs heat the atmosphere but then quickly reverses his position and states "the car and outside fumes like actually heat it up and then the CFCs they actually eat the ozone layer." Elizabeth, who also uses ozone depletion to explain the greenhouse effect, explicitly describes that the greenhouse effect was "hurting the planet" and "bad for the environment overall." These findings are similar to previously reported student views connecting the greenhouse effect with ozone depletion as being "bad for the environment" (e.g., Boyes and Stanisstreet, 1992; Francis et al., 1993).

Over the course of the interview, Kevin expressed a sense that he knew that the mechanisms of ozone depletion and the greenhouse effect were different but that both likely led to global warming. Elizabeth was still firmly convinced at the end of the interview that greenhouse effect was a bad thing but she was less clear on whether greenhouse gases were responsible for ozone depletion or something different that heated the atmosphere: "If they're [greenhouse gases] also the gases that are, um, depleting the ozone, then it would be connected. But it might be two separate issues that are put together because it's all, like, in the atmosphere." At the very end of his interview, Kevin states: "Skin cancer is just too much ultraviolet rays on your skin and global warming is the heating up of surface temperature." Finally the most interesting transition occurred at the very end of Rebecca's interview when the interviewer asked her to distinguish between the terms ozone depletion, greenhouse gas, and global warming. She had a revelation, stating “You want me to connect them don’t you? I have this awesome idea going!” She then expressed the concept of trapping energy for the first time in the entire interview:

> What I’m thinking is the ozone depletion has to do, once again, with gases and things that you have in the ozone layer. Um, greenhouse effect would be about the gases, I don’t know if I said this before, but the gases have, not gases, what am I talking about, um, UV rays and such, have a certain amount of energy and by the time they hit the earth, they, and bounce back off, go back out in space they don’t have enough energy to get back out, so they end up just staying, which would be the greenhouse effect, so, all the heat and energy just ends up staying in the earth, instead of going back out to holes in the ozone layer, um, which, in turn, creates global warming cause there more heat and energy bouncing around the atmosphere than there normally would have been.

It was almost as if the addition of the terms “ozone depletion” and “global warming” provided new labels that Rebecca then use to re-describe several of her previous answers. Consistent with the literature about the conflation of these ideas (e.g., Francis et al., 1993; Gowda et al., 1997), Rebecca self-reports that she “was definitely kind of pulling it all together when I first explained it.”

Two of the nine students (Melissa and George) presented models that involved both ozone depletion and atmospheric trapping, similar to previously reported student models (Papadimitriou, 2004; Rebich and Gautier, 2005). For Melissa, greenhouse gases are actually the things being trapped:

> I guess I would have said something about the ozone layer and the ozone hole and it allows more light and more energy to reach the earth's atmosphere, and then I would've talked about how, how pollutants and other products of human activity, those kinds of energy are being trapped in by certain gases in the atmosphere.

It was confirmed that she felt the pollutants and greenhouse gases were being trapped and that these "have heat and energy." George initially described that burning of fossil fuels released emissions that didn't let as much energy leave the atmosphere and trapped energy from the Sun. However, he very quickly interjected, "Oh, wait, wait, and, I just know this from a TV show. I guess it's, like, O3." He then described the ozone hole and destruction of the ozone layer.

While George retained both ozone depletion and trapping mechanisms in his description at the end of the interview, he clarified that the energy was "temporarily trapped. There's energy leaving and going out all the time." This emphasis was added in response to discussions earlier in the interview. It is unclear how Melissa's views changed over the course of the interview because her quote above was actually from the end of the interview and she had not been asked a complementary question at the beginning.

The remaining four students (Conan, Melissa, Paul, and Raoul) provided introductory descriptions much more closely, although not perfectly, aligned with scientific models of the greenhouse effect. Conan had just learned about the greenhouse effect in a second university class he was taking. He explained that "the atmosphere holds in heat from the Sun" and that burning of coal and carburetors of cars "form a layer of a different kind of gas inside the atmosphere, or a high concentration of it, and so the heat can't escape as much from the atmosphere as it should." He also mentioned the concept of energy balance. Farah described a "foggy shield in the atmosphere, upper atmosphere . . . that tends to trap heat inside with layers, outer layer and the Earth, and creates increased temperatures and climate change." Further probing regarding the location of this shield eventually illustrated that Farah thought the shield was high up but that gases throughout the atmosphere below the shield trapped energy. Paul provided a very thorough explanation and included the most scientific terminology:

> I believe that the greenhouse effect is caused by electromagnetic radiation from something, such as the Sun, probably just only the Sun, entering our fairly thick atmosphere that, ah, the electromagnetic rays, radiation in at least one of the forms, at least of the spectrums, is able to penetrate through whatever there are, the clouds and whatever elements are in the atmosphere. And upon hitting the ground (the surface) they will be converted into heat energy, thermal energy. And, due to the, whatever, however dense, or whatever the chemical make up of the atmosphere is, the heat gets physically trapped inside. So essentially, it's electromagnetic radiation coming in, turning into heat and then being trapped in there . . . it's very similar to the way that light enters a glass greenhouse, and, ah, turns into, from electromagnetic radiation, visible, and whatever else it penetrates, into heat energy and being trapped inside. So, the result is the interior, whatever it is, being covered by the atmosphere, or the glass, is much hotter than what it would normally be.

Finally, Raoul also provided a trapping model, although he used the caveat that "nothing is a perfect absorber of energy" to justify the claim that the planet radiates away less than it receives:

> More energy gets trapped in the Earth's atmosphere, the Earth obviously receives most of its energy, pretty much all of it, from the Sun. Ah, the greenhouse effect would be it can radiate away less of that than it receives, or I guess it would always radiates away less than it receives . . . making the planet hotter as a whole."

While none of these four students described ozone depletion models initially, several of them did describe models of ozone depletion while going through the misconception survey. The most obvious of these was Conan, whose recently acquired definition for the greenhouse effect had not yet been firmly established. Indeed, by the third item of the survey, Conan described that the main source of heat at Earth's surface was ultraviolet light passing through the ozone layer. He explained that "ultraviolet stuff that does pass through the ozone layer is the problem with global warming." Throughout the remainder of the interview, he provided descriptions consistent with ozone depletion. His final comment was "I know the ozone is a thin layer around the Earth and its part of the atmosphere and, to my understanding, it is part of the greenhouse effect. Um, yes, yes, yeah."

While Paul maintained a mental model of thermal energy being trapped in Earth's atmosphere, he expressed several misconceptions about physics throughout his interview. He presented the model that lower energies of light traveled less far and are weaker than higher energies of light, explaining that that radio waves from the Sun are:

> not as strong once they reach the Earth, probably because we are 93 million miles away, and, ah, they are a lower energy, so, they possible could die out.

He also described that the ozone is a low pass filter that absorbs ultraviolet through gamma ray energies while the atmosphere is a high pass filter that blocks radio energies. When posed with the hypothetical scenario that Earth had no ozone layer, Paul stated that "gamma rays and x-rays would . . . do most of the heating because they're the highest energy." Halfway through the interview, he also was swayed by the distracter of ozone depletion and recalled hearing "in the news that greenhouse gases are eating the ozone or destroying the ozone or chemically reacting with the ozone to form non-ozone substances . . . Destroying the ozone layer would definitely allow more high energy radiation levels to enter the atmosphere and thus it would alter the Earth's temperature, heating up, heating it." Most interesting of all, Paul explained that "thermal energy is definitely a form of energy that needs a medium, and the atmosphere is definitely a good medium." When asked if this thermal energy has difficulty getting out of the atmosphere, Paul described that the energy cannot get out as thermal energy because "the space outside of it [the Earth] is pretty close to a void and so there isn't anywhere for it to go." Thus, while Paul provided the an terminology-rich description of the greenhouse effect at the beginning of his interview, his mechanism for trapping thermal energy in the atmosphere was not based upon optical properties of greenhouse gases but rather a misconception that thermal energy is trapped because there is no a medium to carry it away into space.

Farah provided a fairly solid understanding of the greenhouse effect throughout her interview. In particular, she was confident that ozone depletion was not a part of the greenhouse effect. Several time throughout the interview, she explained that ozone was "a whole separate issue" and she didn't think that ultraviolet light passing through the ozone layer was the "main source of heat for the Sun and planet." For GECI.vB2 Item 28, she immediately eliminated the distracter of the ozone hole that tripped up Paul. She then provided a very insightful meta-cognitive reflection: "I think I remember learning in, in school, in high school, or maybe even having this problem myself, but the issue of the ozone layer and the greenhouse effect are commonly considered to be just one and the same when, in fact, they're not." Farah attributed her understanding of the greenhouse effect to her "very environmentally and politically active family" and to her high school chemistry teacher. She described that, in addition to drawing lots of pictures and singing songs about science topics, her high school chemistry teacher "went in knowing that, knowing that a lot of us would have the misconception that they're one and the same thing, and we just concentrated on, on both of them, um, separately." This teaching strategy of directly addressing both ozone depletion and the greenhouse effect as separate issues, as recommended by Rye et al. (1997), appears to have worked in Farah's case.

Finally Raoul provided consistently accurate descriptions throughout his interviews. For example, Raoul had heard of ozone depletion but did not accept it as a mechanism for heating the Earth. However, Raoul did have some difficulty fully accepting that the amount of energy leaving Earth is exactly equal to incoming energy because "nothing is a perfect absorber of energy." He thought it was probably "close to equal" but vacillated throughout the interview between the amount of energy leaving being slightly more and slightly less than the energy received. His ideas were still much more developed and sophisticated than those of other interviewees and he was less swayed by distracters throughout the survey.

A final point is that students refer to the media, teachers, friends, and parents as sources of information about the greenhouse effect. Rebecca thought the Sun mostly gives off ultraviolet energy because "mostly because it's the one that I know the most about . . . in terms of obviously like sunscreen and things, it has to be present in our atmosphere in order for me to have heard about it." Throughout his interview, Kevin struggles with his sense that the greenhouse effect, ozone depletion, and global warming are different phenomena. However, when asked if the media distinguishes between the three concepts, he firmly stated that they do not "because they all talk about them the same way. Because they're all bad and they all cause the same thing to the media."

Conan attributes his knowledge to the media, teachers, and friends. “I've always heard that ultraviolet's the problem from, again, they, the people that tell me, um, the teachers, peers, the news, whatever specialist comes on and says ultraviolet is the problem. It just seems, like, ingrained in my skull.” Finally, Melissa and Rebecca both refer to a discussion in the planetary science course from which they were recruited. For both of them, the discussion in this class about the EM spectrum actually re-enforced the misconception that the Sun mostly gives off ultraviolet energy. This is likely due to discussions about ultraviolet through gamma ray light having more energy.

Interested readers are again referred to Appendix D for a detailed summary of the interview transcripts. Again, the primary purpose of these interviews was to inform the development of the GECI survey instrument and to validate the manner in which students interpreted the items on this survey. The remainder of this chapter describes the development and analyses of the GECI survey.

3.3 Response Frequencies to GECI Items Grouped by Themes

Validation of the GECI.vC survey instrument is discussed in Chapter 4. The remainder of this chapter presents response frequency distributions to all GECI survey items. Survey items have been grouped by concept themes, with related questions from all three survey versions being presented together to show the development and evolution of GECI survey items. Presented for each item are both the wording of the item as it appeared on the student survey and a graph showing the response frequency distribution both before and after instruction. All pre-instruction responses have been grouped together based upon the assumption that the various classes sampled the same population of non-science majors. Post-instruction responses have been separated into two groups: classes that did not cover the greenhouse effect and classes that did treat the greenhouse effect. With the latter grouping, different types of instructional interventions occurred in each of these classes. The post-instruction response frequency distribution is provided here to indicate whether the surveys show changes as a result of instruction. A more detailed investigation of specific interventions is saved for Chapter 4.

Results from student written explanations provided on a subset of the GECI.vA surveys and from student interviews covering the survey items on GECI.vB were also summarized. Both of these qualitative datasets provided insights into student thinking about the greenhouse effect and guidance for the development of subsequent versions of the GECI.

As described previously in Chapter 2, the most common student models for understanding the greenhouse effect mechanism involved either an increase in the amount of energy penetrating the atmosphere (often associated with ozone depletion) or an decrease in the amount of heat leaving the Earth system to space (often due to trapping of either energy or gases). In the latter case, only rarely did students correctly describe that infrared energy is absorbed and re-emitted by greenhouse gases. Instead, it was much more common for students to describe that energy bounced or reflected in the atmosphere. Also, it was uncommon for students to describe that energy left the Earth system to space. Rather, SSR descriptions tended towards models in which energy was permanently trapped in the atmosphere. The beliefs and reasoning difficulties were incorporated into GECI survey items dealing with student models for the greenhouse effect (Section 3.4), the types of energy associated with the Sun and Earth's atmosphere and surface (Section 3.5), energy balance between Earth and space (Section 3.6), and reflection versus absorption of light (Section 3.7).

In addition, student SSR responses indicated a strong student tendency to associate and intermix the greenhouse effect, global warming, ozone depletion, and air pollution. The surveys also elicited student beliefs regarding the types, sources, and appearance of greenhouse gases and consequences of the greenhouse effect. These themes were incorporated in the GECI survey versions through items requiring students to discriminate between the greenhouse effect and global warming (Section 3.9) and to identify and characterize greenhouse gases (Section 3.8). GECI survey items regarding sources for greenhouse gases (Section 3.10) and consequences of the greenhouse effect (Section 3.11) were developed and tested but ultimately removed from GECI.vC due to practical restrictions on survey length as well as attempts to focus the survey instrument more specifically on the greenhouse effect rather than the enhanced greenhouse effect and climate change.

3.4 Student Models for the Greenhouse Effect

Several items on the GECI survey were developed to address student models regarding the greenhouse effect. In addition to providing the two most common models involving penetration and trapping of light, several other distracters from the SSR surveys were used. Table 3.3 below shows the first multiple-choice items on greenhouse effect models that were developed and tested on Survey GECI.vA.

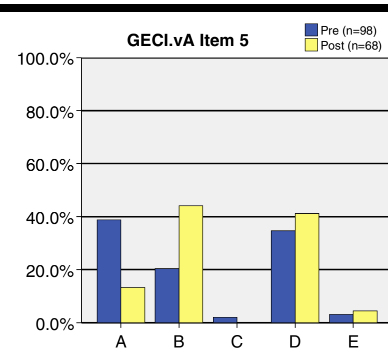
The table format below is used throughout the remainder of the chapter to provide both the wording and pre- and post-instructional response frequencies for each survey item shown. The correct answer is printed in bold-face font. The graph shows the percentage of students who selected each response option pre-instruction (darker bars) and post-instruction (lighter bars). Pre-instruction distributions may be spread evenly among the response options or may be more heavily concentrated on particularly popular distracters targeting incorrect mental models that the question is designed to elicit and test. Ideally, the post-instruction distribution should show a shift towards the correct answer. The legend also provides the number of students who answered each survey item.

Table 3.3 Responses regarding greenhouse effect models (GECI.vA)

<u>GECI.vA: Item 5</u>

Greenhouse gases raise Earth's overall surface temperature by

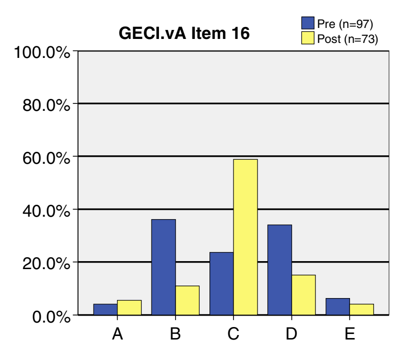
a) destroying the ozone layer and allowing more sunlight into the atmosphere.
b) affecting the flow of energy through the atmosphere.
c) causing an increase in the amount of clouds and rainfall.
d) trapping heat permanently in the atmosphere.
e) magnifying and focusing sunlight in the atmosphere.



<u>GECI.vA: Item 16</u>

With the greenhouse effect, which of the following most strongly affects Earth's overall surface temperature?

a) heat released by factories and other industrial activities
b) ultraviolet light passing through the ozone hole
c) infrared light that is absorbed and then given off by gases in the atmosphere
d) air pollution trapped in the atmosphere by greenhouse gases
e) gas molecules circulating in the atmosphere because hot air rises



Pre-instruction results for GECI.vA Item 5 confirm student beliefs involving ozone depletion (38%) or trapping of heat (35%) before instruction. The word "permanently" did not dissuade students from selecting Option D. Post-instruction results reveal a shift from ozone depletion towards the less intuitive but more accurate Option B (44% post-instruction). However, post-instruction selections involving permanent trapping are still robust after instruction (41%). The number of correct response regarding the flow of energy doubled from 20% and 44% through instruction.

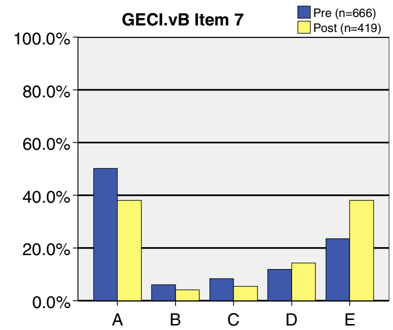
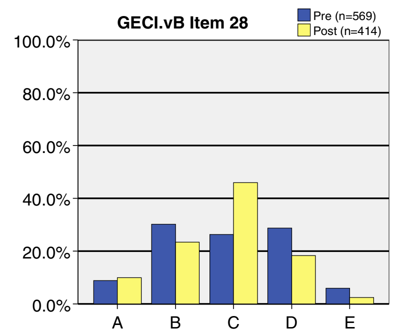
On MCER surveys, students were asked to explain the reasoning behind their multiple-choice responses. MCER written explanations to Item 5 were consistent with student responses on SSR surveys. Students describe that it made sense that a hole in the ozone layer would increase temperatures on Earth, through comments like "More Sun = more heat and higher temps" and "Because ozone layer gets a big hole more ultraviolet of Sun goes into the Earth." One student described that the ozone hole affects both incoming and outgoing energy but still associates ozone depletion with overall heating: "This hole lets in more ultraviolet light during the day making it warmer. At night, the Earth loses more heat than normal because it escapes through the hole." Some students selecting Option D regarding permanent trapping revealed student beliefs that both energy and gases are trapped, with comments like "The gases don't allow the hot air and the heat energy to rise out of the troposphere" and "Greenhouse gases stay in the atmosphere without moving." They also commonly discussed reflection of light rather than absorption, stating "rather than the heat escaping, it bounces around inside of atmosphere" and "I remember seeing a picture of light bouncing between the atmosphere and the surface." Students who selected the correct choice regarding the flow of energy through the atmosphere gave responses that involved absorption and retention of energy rather than reflection and also used reasoning strategies to eliminate certain options ("It doesn't trap heat permanently or we'd all fry" and "It doesn't destroy ozone and I don't think it has anything to do with rainfall, it either traps heat or just increases the flow.")

One student selecting Option D to Item 5 described that the trapped heat came from factories, stating "When heat is trapped in our atmosphere, this causes warmer temperature because they come from factories in which they produces heat." This was actually one of the distracters provided on Item 16 above. This second item confirms the strong student association with trapping of actual matter, in this case air pollution, by greenhouse gases. This was the second most popular choice (34%) after ozone depletion (36%) pre-instruction. The question also shows a strong shift towards the correct response regarding infrared light, with responses moving from 24% to 59% through instruction. Student models involving heat from factories, clouds and rainfall, and magnification of light were present but at lower levels (<5%).

On Item 16, student written responses for Option A regarding heat released by factories were similar to explanation for Option D regarding trapping of pollution. These explanations commonly associated pollution with heat and mentioned that both get trapped ("I think that the air pollution gets trapped and causes the heat from pollution not to escape Earth's atmosphere." "The air pollution traps under the ozone, and when the hot air rises, it gets trapped." "They (industry) release the heat into the air, which retain the heat and warm the air.") Student selecting ozone depletion repeated comments about having heard about ultraviolet energy, knowing that it was harmful, and thinking that the Sun mostly gives off UV ("UV light is what everyone is so worked up about all the time so I just figured it has the most important affect on Earth's surface." "I know that ultraviolet light is a bad thing and that's why I wear sunscreen." "The ozone being depleted and the Earth being hit directly by ultraviolet light would raise the temperature by more than anything.") Students who selected the correct answer to this item provided varying levels of accuracy regarding permanent versus temporary trapping and reflection versus absorption of energy. As an example, one student correctly describes temporary trapping but invokes reflection: "When light travels into our atmosphere it is temporarily "contained" by our atmosphere. It bounces around between our surface and the atmosphere heating the surface temp."

The two survey items discussed above were slightly revised based upon these results. Due to the low response frequency to GECI.vA Item 5 option regarding clouds and rainfall, this was replaced by a model involving a "localized" greenhouse effect resulting from smog and pollutants over populated cities for GECI.vB Item 7. Permanent trapping of heat was also revised to test a distracter involving plants and photosynthesis. For GECI.vA Item 16, the terms "ultraviolet light" and "infrared light" were changed to the more generic terms "sunlight" and "energy" in an attempt to see how much of student selection was biased by this term. Table 3.4 shows the two survey items related to greenhouse effect models tested on Survey GECI.vB.

Table 3.4 Responses regarding greenhouse effect models (GECI.vB)

GECI.vB: Item 7 Greenhouse gases affect Earth's overall surface temperature by a) destroying the ozone layer and allowing more sunlight into the atmosphere. b) altering how quickly plants carry out photosynthesis. c) concentrating smog and pollutants over populated cities. d) magnifying and focusing sunlight in the atmosphere. **e) influencing the flow of energy through the atmosphere.**	
GECI.vB: Item 28 With the greenhouse effect, which of the following most strongly affects Earth's overall surface temperature? a) heat released by factories and other industrial activities b) more sunlight passing through the ozone hole **c) energy that is absorbed and then given off by gases in the atmosphere** d) air pollution trapped in the atmosphere by gases e) gas molecules circulating in the atmosphere because hot air rises	

Because the distracter involving trapping of heat has been removed, even more students (50% pre-instruction) selected ozone depletion on GECI.vB Item 7 compared to GECI.vA Item 5 (34% pre-instruction). The other three distracters (photosynthesis, smog, and magnification of light) are all selected by over 5% of students pre-instruction. The percentage of pre-instruction students selecting the correct answer about influencing the flow of energy (24%) does not change significantly from results on GECI.vA Item 5 (20%). Student interviews did not raise concerns about student misinterpretation of the item. As described in Section 3.2 above, the item distracted Paul (Interview #4) into discussing ozone depletion more during his interview. Another student, George (Interview #6) correctly selected Option E, explaining that this option went with his model and was a more generic statement consistent with ozone depletion Option A and magnification Option D.

Comparing GECI.vB Item 28 with GECI.vA Item 16, making the terms ultraviolet and infrared light more generic by using “sunlight” and “energy” did not change the shape of the pre-instruction histograms significantly. However, following instruction, less student selected the correct response for the item on GECI.vB (46%) than on GECI.vA (59%). It is unclear if these changes were due solely to the wording and placement of the item on the survey or other factors, such as differences in instructional interventions. However, three out of five students interviewed on this item expressed concern over the wording of the correct response. Melissa (Interview #1) explained, “Answer C, I don’t exactly understand it.” During Interview #5, Conan did not select Option C because it seemed like a distracter and sounded “like something written to sound right.” Farah (Interview #8) stated “I’m just reluctant just because I don’t know how to interpret being, like, energy being given off by gases after being absorbed in the atmosphere. That’s a lot of things going on.”

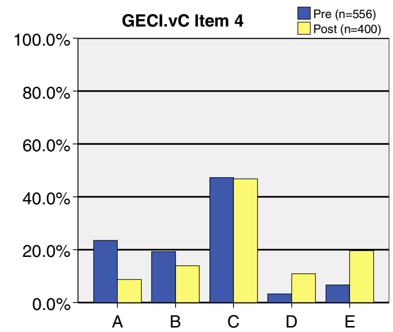
Based upon this interview data, the wording of this item was revised on GECI.vC Item 11. Additionally, three survey items were included rather than two (see Table 3.5).

Table 3.5 Responses regarding greenhouse effect models (GECI.vC)

GECI.vC: Item 4

Which of the following is a primary characteristic of greenhouse gases?

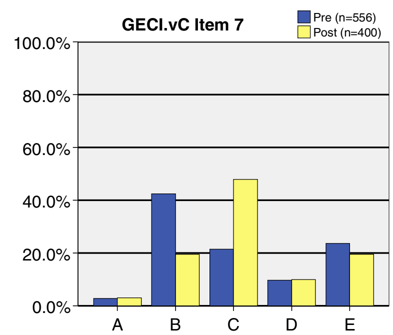
a) They can destroy certain molecules in the atmosphere.
b) They bend and magnify sunlight entering the atmosphere.
c) They can trap certain molecules in the atmosphere.
d) They can bounce around more in the atmosphere.
e) They are transparent to some forms of energy but not all.



GECI.vC: Item 7

Which of the following most strongly affects Earth's overall surface temperature?

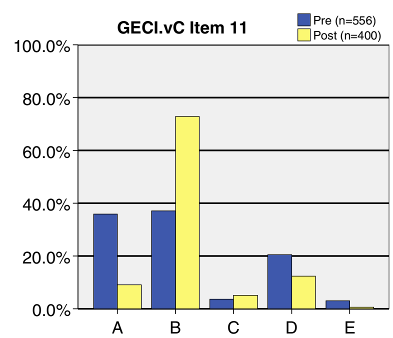
a) heat released by factories and other industrial activities
b) the destruction of the ozone layer allowing more sunlight into the atmosphere
c) the flow of different forms of energy through the atmosphere
d) air pollution trapped in the atmosphere by gases
e) sunlight being magnified and focused by gases in the atmosphere



GECI.vC: Item 11

A planet that has a greenhouse effect

a) receives more UV sunlight because it lacks ozone in its atmosphere.
b) has an atmosphere that absorbs and then gives off certain forms of energy but not all.
c) receives more energy because it is closer to its central star.
d) has an altered atmosphere due to living organisms.
e) does not radiate any energy away into outer space.



While GECI.vC Item 7 is most similar to GECI.vA Item 16 and GECI.vB Item 28, significant revisions were made. The stipulation regarding the "greenhouse effect" has been dropped from the stem, the wording regarding ozone depletion has been slightly modified, the option regarding circulating gases has been replaced by a model involving magnification and focusing of sunlight, and the correct response regarding absorption and re-emission of energy has been replaced by the previously discussed option regarding "the flow of different forms of energy through the atmosphere." The item shows a higher pre-instruction response frequency for the ozone depletion model (from 36% and 30% on the first two versions to 44% on GECI.vC). All distracters are still selected by at least ~5% of students pre-instruction, although fewer students selected "heat released from factories" (4.7%) when given the option of sunlight being magnified and focused by the atmosphere.

GECI.vC Item 4 was related to previous survey items, but represented an attempt to become more specific about the behavior of greenhouse gases. The correct answer deals with wavelength dependent transmission of energy. The most popular choice, both before and after instruction, was that greenhouse gases trap certain molecules in the atmosphere (44%), although the students may have been overly influenced by the term "trap" and not differentiated between trapping molecules and trapping energy. Other popular pre-instructional choices involved ozone depletion (24%) and magnification of energy as it enters the atmosphere (21%). This question resulted in only moderate instructional gains, with many students holding firmly to the response regarding trapping. Also, this item received a comment from an expert reviewer that all gases are transparent to some forms of energy but not all (see Section 4.6). Both of these are important factors to consider in deciding whether to keep this question in the final GECI (see Chapter 4).

Item 11 references any planet with a greenhouse effect, but contains similar models as addressed before – including UV light penetrating through ozone, alteration of the atmosphere by living things, permanent trapping asked in the form of not radiating energy to space. As discussed above, the correct response from GECI.vA Item 16 and GECI.vB Item 28 was reworded in response to interview data. Ultraviolet penetration in the absence of ozone was still a popular pre-instruction choice (36%), but the correct response was equally popular – and more popular that on previous survey versions (23% and 26% on the first two versions and 36% on GECI.vC). The new distracters of being closer to the central star and not radiating any energy away to space were selected 4% and 6% prior to instruction, respectively. Post-instruction surveys show a significant shift from ozone depletion towards absorption and re-emission of certain forms of energy.

To summarize, the items related to student models for the greenhouse effect all reveal strong student associations both with an increase in solar penetration due to ozone depletion and some form of trapping in the atmosphere, even if it involves gas molecules and pollution rather than energy. Results from this work are consistent with previous research (e.g., Boyes and Stanisstreet, 1992; Boyes and Stanisstreet, 1993; Papadimitriou, 2004; Rebich and Gautier, 2005). Magnification of energy through the atmosphere was also a common belief that was expressed more frequently on the GECI surveys than on SSR surveys, especially on GECI.vC Item 7. The weakest distracters involved clouds and rainfall, plants and photosynthesis, gas molecules circulating in the atmosphere, and changing the distance to a planet's central star. To improve the item distracters on the final GECI, it may be beneficial to resurrect the distracter from Survey GECI.vA Item 5 regarding trapping of heat permanently in the atmosphere. Other possible revisions to the final version of the GECI are discussed further in Section 4.8.

3.5 Types of Energy Associated with Sun, Atmosphere, and Surface

Several survey items required students to select the form of energy they most associated with three important components of the greenhouse effect: the Sun, Earth's atmosphere, and Earth's surface. The basis for these items was to quantify how students discriminate between various forms of energy involved in the greenhouse effect both before and after instruction. Previous research indicates that students often do not distinguish between incoming solar energy and outgoing terrestrial energy (Dove, 1996; Papadimitriou, 2004; Rebich and Gautier, 2005; Gautier et al., 2006). This was investigated more thoroughly here using a battery of questions involving types of energy.

3.5.1 Energy Given Off by Sun

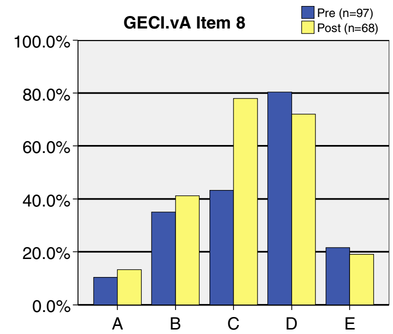
First, it was determined that student beliefs regarding the form energy given off by the Sun provides an important foundation for student reasoning regarding the heating of Earth's atmosphere. While it was difficult to quantify from SSR surveys the types of energy student felt was coming to the Earth system from the Sun, students commonly associated sunlight with either heat or higher energy forms of light such as ultraviolet and x-ray light. Student beliefs on this were made more quantitative through use of the following survey items on different versions of the GECI shown Table 3.6.

Table 3.6 Responses regarding main type of energy from Sun

GECI.vA: Item 8

The Sun mainly gives off which of the following forms of energy? Circle all that apply.

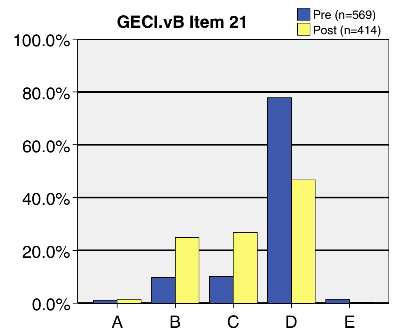
a) radio
b) infrared
c) visible
d) ultraviolet
e) z-ray



GECI.vB: Item 21

The Sun mainly gives off (radiates) which form of energy?

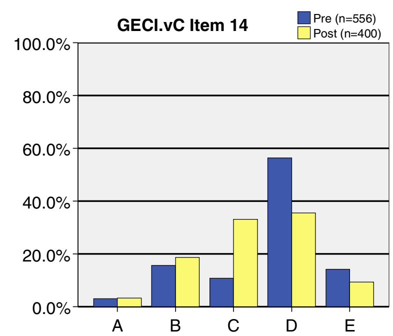
a) radio
b) infrared
c) visible
d) ultraviolet
e) z-ray



GECI.vC: Item 14

At which of the following does the Sun give off (radiate) energy at its maximum intensity?

a) radio
b) infrared
c) visible
d) ultraviolet
e) z-ray



Note that the item did not change significantly between the three survey versions. On GECI.vA Item 8, students were allowed to circle all choices that apply. The wording on this item was revised to clarify that the term "given off" is equivalent to "radiates" on GECI.vB Item 21. This item was further revised on GECI.vC Item 14 to more explicitly focus students' answers on the energy radiated at the maximum intensity by the Sun.

This second change was necessary because as worded on Survey GECI.vB Item 21, both visible and infrared were comparably good answers.

The vast majority of students surveyed pre-instruction believe that the Sun mostly gives off ultraviolet energy, with visible and infrared as secondary choices. When given the option to circle all that apply on GECI.vA Item 8, 80% of pre-instruction students selected ultraviolet in addition to other forms of energy. On the other two surveys, ultraviolet was selected 78% and 56% on pre-instruction surveys, between 3-8 times more frequently than infrared and visible. The overwhelming explanation of student reasoning behind this selection involved media and advertising attention the health risks associated with exposure to ultraviolet light. The following student quotes from GECI.vA Item 8 express this reasoning:

> UV rays are very harmful to the Earth, they can actually be deadly. Without the ozone layer we would burnt to a crisp.
>
> The Sun gives off UV rays because you always hear about how harmful it is to us.
>
> It's a known fact that the Sun gives off this energy. Too much of it is not good for your skin. That's why doctors always tell people to wear Sun screen.

During student interviews, students stated that they had selected ultraviolet because it was the energy they had heard most about (including references to sunscreen, sunburns, and sunglasses) and visible because they could see sunlight. Two students, Melissa (Interview #1) and Rebecca (Interview #2) referred to discussion about the EM spectrum in their planetary science class as reinforcing the idea that that the Sun gives off high energy ultraviolet energy. Only one student, Farah (Interview #8) selected infrared because she associated infrared and the Sun with "heat."

Additionally, student beliefs were resistant to change. For the two latter GECI surveys, in which students could select only one answer, the most popular choice was still ultraviolet post-instruction (47% and 38%). On GECI.vA Item 8, the post-instruction percentage of responses for ultraviolet (72%) remained high and was only marginally below that for visible light (78%).

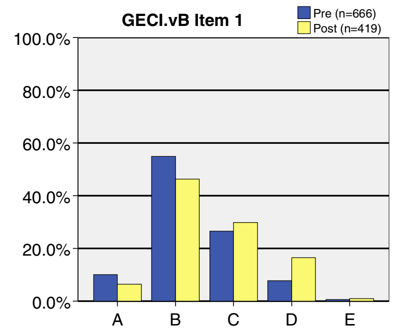
The strategy behind allowing multiple responses on GECI.vA Item 8 was to determine which forms of energy students most frequently associate with the Sun without test bias. Based upon these results from this item, a second survey item focusing more specifically on infrared, ultraviolet, and visible energy from the Sun was developed. This item asked students to select the two main form of energy given off by the Sun. The pre- and post-instruction responses for this item are shown in Table 3.7 below.

Table 3.7 Responses regarding 2 main types of energy from Sun

GECI.vB: Item 1

The Sun mainly gives off (radiates) which two forms of energy?

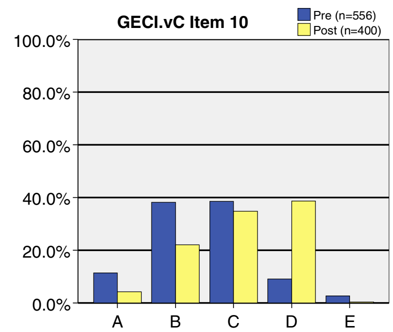
a) ultraviolet and x-ray
b) ultraviolet and infrared
c) visible and ultraviolet
d) infrared and visible
e) radio and infrared



GECI.vC: Item 10

The Sun mainly gives off (radiates) which two forms of energy?

a) ultraviolet and x-ray
b) ultraviolet and infrared
c) visible and ultraviolet
d) infrared and visible
e) radio and infrared



While over 90% of the energy from the Sun is radiated at visible and infrared energies, only 8% of students selected this option on either of the pre-instruction surveys. Options involving ultraviolet energy were much more popular, accounting for over 90% of all pre-instruction survey responses. While more pre-instruction students selected ultraviolet with infrared (55%) than ultraviolet with visible (27%) on GECI.vB Item 1, students were equally split between ultraviolet and visible (39%) and ultraviolet and infrared (39%) on GECI.vC Item 10. Since the items were identical on both versions of the survey, it is unclear why the pre-instruction distributions differ. Possible explanations include the placement of the item at the beginning of GECI.vB and in the middle of GECI.vC, and differences in the timing of survey administration (the GECI.vC pre-instruction survey was administered later in the semester). Larger learning gains were seen on GECI.vC (which shifted to 36% post-instruction) than for GECI.vB (which increased to 17%). This is likely due to differences in instructional interventions between the classes in different semesters. However, answers involving ultraviolet light with visible and infrared were still popular post-instruction during both semesters.

Interviews confirmed that students did not have difficulty interpreting this survey item. Students were familiar with the types of EM radiation listed and provided examples, including infrared cameras and the adaptation of the human eye to detect visible light.

The student belief that the Sun mainly gives off ultraviolet energy strengthens student tendencies to associate atmospheric surface temperatures and the greenhouse effect with the phenomenon of ozone depletion. If the Sun was giving off most of its energy at ultraviolet energies, ozone depletion would lead to increased surface temperatures in addition to causing a skin cancer health risk. The findings presented here complements previous research indicating that students associate ultraviolet energy with thermal energy (Christidou and Koulaidis, 1996). Students know that the Sun is hot and associated most of this heat with ultraviolet energy.

3.5.2 Energy Absorbed and Given Off by Atmosphere

Students were also asked about the main form of energy absorbed by and given off by Earth's atmosphere and surface. The same five options were provided for each item (radio, infrared, visible, ultraviolet, and x-ray). In addition, for items regarding Earth's surface, a distinction was made on some surveys between energy radiated during daytime and nighttime. Table 3.8 and Table 3.9 summarize the pre- and post-instructional responses for each of these items, respectively. The most common response for each item has been highlighted in bold-face font. Note also that the sum of percentages is >100% for items from GECI.vA because students were able to circle more than one answer on this survey version. This was done intentionally during on the preliminary multiple-choice items so that survey would not bias student choices.

Table 3.8 Pre-instruction responses regarding energy in atmosphere and at surface

Item Description	Survey Version & Item	Radio	IR	VIS	UV	X-ray
Earth's atmosphere is heated mainly by which of the following forms of energy? Circle all that apply.	GECI.vA: Item 6 (n=97)	10%	35%	37%	**72%**	9%
Earth's atmosphere absorbs and is heated by mainly which form of energy?	GECI.vB: Item 5 (n=666)	2%	21%	6%	**69%**	2%
Earth's atmosphere is warmer than it would be without a greenhouse effect. Which form of energy is absorbed by the atmosphere and mainly causes this increased temperature?	GECI.vC: Item 2 (n=556)	1%	21%	4%	**71%**	2%
Earth's atmosphere mainly gives off which of the following forms of energy? Circle all that apply.	GECI.vA: Item 15 (n=103)	20%	47%	31%	**54%**	11%
Earth's atmosphere mainly gives off (radiates) which form of energy?	GECI.vB: Item 13 (n=666)	14%	**33%**	14%	**33%**	7%
	GECI.vC: Item 17 (n=556)	15%	**37%**	19%	16%	14%*
Earth's surface is heated mainly by which of the following forms of energy? Circle all that apply.	GECI.vA: Item 17 (n=97)	3%	40%	23%	**76%**	1%
Earth's surface mainly gives off (radiates) which form of energy?	GECI.vB: Item 30 (n=569)	14%	**38%**	26%	16%	6%
Most of the energy bouncing (reflecting) off Earth's surface is in which form of energy?	GECI.vB: Item 29 (n=569)	13%	28%	21%	**31%**	6%
During the daytime, Earth's surface mainly gives off which of the following forms of energy? Circle all that apply.	GECI.vA: Item 11 (n=103)	18%	43%	28%	**55%**	9%
During the daytime, Earth's surface mainly gives off (radiates) which form of energy?	GECI.vB: Item 9 (n=666)	11%	**34%**	25%	26%	3%
	GECI.vC: Item 20 (n=556)	11%	28%	**35%**	21%	5%
During the daytime, most of the energy bouncing or reflecting off Earth's surface is which of the following?	GECI.vB: Item 8 (n=666)	6%	21%	24%	**46%**	3%
During the nighttime, Earth's surface gives off mainly which of the following forms of energy? Circle all that apply.	GECI.vA: Item 4 (n=98)	18%	**63%**	17%	16%	10%
During the nighttime, Earth's surface mainly gives off (radiates) which form of energy?	GECI.vB: Item 10 (n=666)	15%	**50%**	12%	17%	6%
	GECI.vC: Item 6 (n=556)	13%	**53%**	7%	15%	12%

*Survey item changed from "x-ray" to "Earth's atmosphere does not give off energy."

Table 3.9 Post-instruction responses regarding energy in atmosphere and at surface

Item Description	Survey Version & Item	Radio	IR	VIS	UV	X-ray
Earth's atmosphere is heated mainly by which of the following forms of energy? Circle all that apply.	GECI.vA: Item 6 (n=68)	2%	**74%**	72%	29%	2%
Earth's atmosphere absorbs and is heated by mainly which form of energy?	GECI.vB: Item 5 (n=419)	2%	**42%**	16%	39%	1%
Earth's atmosphere is warmer than it would be without a greenhouse effect. Which form of energy is absorbed by the atmosphere and mainly causes this increased temperature?	GECI.vC: Item 2 (n=400)	1%	**59%**	8%	31%	1%
Earth's atmosphere mainly gives off which of the following forms of energy? Circle all that apply.	GECI.vA: Item 15 (n=72)	7%	**68%**	39%	17%	1%
Earth's atmosphere mainly gives off (radiates) which form of energy?	GECI.vB: Item 13 (n=419)	7%	**52%**	14%	24%	3%
	GECI.vC: Item 17 (n=400)	8%	**63%**	14%	9%	6%*
Earth's surface is heated mainly by which of the following forms of energy? Circle all that apply.	GECI.vA: Item 17 (n=73)	0%	45%	**73%**	30%	0%
Earth's surface mainly gives off (radiates) which form of energy?	GECI.vB: Item 30 (n=414)	6%	**62%**	14%	15%	3%
Most of the energy bouncing (reflecting) off Earth's surface is in which form of energy?	GECI.vB: Item 29 (n=414)	6%	**42%**	25%	24%	3%
During the daytime, Earth's surface mainly gives off which of the following forms of energy? Circle all that apply.	GECI.vA: Item 11 (n=72)	4%	**83%**	33%	13%	1%
During the daytime, Earth's surface mainly gives off (radiates) which form of energy?	GECI.vB: Item 9 (n=419)	4%	**52%**	21%	21%	2%
	GECI.vC: Item 20 (n=400)	5%	**61%**	23%	10%	1%
During the daytime, most of the energy bouncing or reflecting off Earth's surface is which of the following?	GECI.vB: Item 8 (n=419)	5%	28%	**35%**	31%	1%
During the nighttime, Earth's surface gives off mainly which of the following forms of energy? Circle all that apply.	GECI.vA: Item 4 (n=68)	9%	**90%**	12%	7%	6%
During the nighttime, Earth's surface mainly gives off (radiates) which form of energy?	GECI.vB: Item 10 (n=419)	7%	**69%**	8%	14%	2%
	GECI.vC: Item 6 (n=400)	7%	**79%**	5%	5%	4%

*Survey item changed from "x-ray" to "Earth's atmosphere does not give off energy."

The top of Table 3.8 reveals that majority (71-74%) of students surveyed pre-instruction believe that the main type of energy absorbed by Earth's atmosphere is the ultraviolet, the same type of energy that most students think the Sun primarily gives off. As one student responding to GECI.vA Item 6 explains, "UV light contains the most energy of the light from the Sun, which is why it provides most of the heat." Student explanations for ultraviolet continued to include descriptions of sunscreen, sunglasses, and the ozone hole. One student selected ultraviolet "because I know from previous classes that the Sun outputs ultraviolet radiation and also sunscreen ads all mention protection from UV rays." Students also referred to ultraviolet energy as being more energetic than other forms of energy: "Ultraviolet light is the most intense of these energies besides x-ray, and x-ray does not get though the ozone." While it is true at the photon level that higher frequency light has higher energy, some students incorrectly translate this understanding to believe that the solar spectrum is also predominantly ultraviolet and x-ray. This was evident in Interview #4 with Paul, who wanted to select gamma rays for heating the atmosphere and settled for x-rays, stating, "They do have a lot of energy, I guess . . . since they have the highest amount of energy, then I'd have to say, of all those choices, x-rays."

Post-instruction responses found on Table 3.9 reveal that students learn that the atmosphere is mainly heated by infrared light as evidenced by their choices on all three surveys. Infrared was the most popular choice post-instruction on all three surveys. While this item does not explicitly discriminate as to the source providing infrared energy, inferences can be drawn from post-instruction responses regarding energy radiated by the Sun and Earth's surface discussed below.

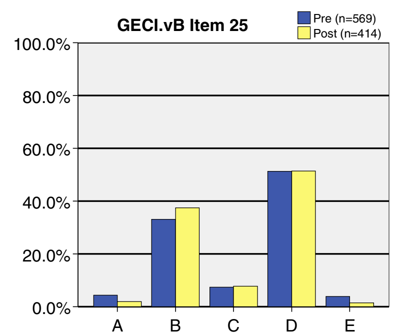
Before examining the remaining survey items on Table 3.8 and Table 3.9, it is informative to look at student responses shown below to two survey items on GECI.vB that differentiated between energy absorbed in the upper atmosphere (stratosphere) and lower atmosphere (troposphere).

Table 3.10 Responses regarding energy heating stratosphere and troposphere

<u>GECI.vB: Item 25</u>

Earth's upper atmosphere (stratosphere) absorbs and is heated mainly by which form of energy?

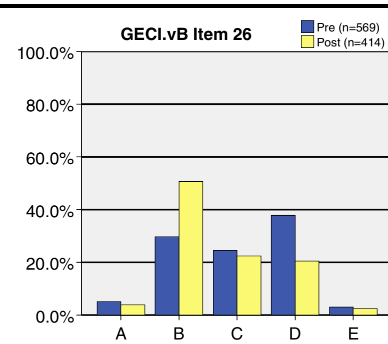
a) radio
b) infrared
c) visible
d) ultraviolet
e) x-ray



<u>GECI.vB: Item 26</u>

Earth's lower atmosphere (troposphere) absorbs and is heated mainly by which form of energy?

a) radio
b) infrared
c) visible
d) ultraviolet
e) x-ray



As Table 3.10 below shows, students most commonly selected ultraviolet energy for both layers pre-instruction, although infrared and, in particular, visible energy were closer contenders when students were asked about the lower atmosphere. Notice also that very little change resulted from instruction with regards to stratospheric heating, while learning gains were shown with regards to tropospheric heating by infrared.

Five students were interviewed regarding these two items. Although one student expressed that she "really didn't know, like I said, the difference between the upper and lower atmosphere," (Melissa, Interview #1) the other four students did not express difficulties describing these two portions of the atmosphere. For the most part, they attributed higher energy processes involving x-ray and ultraviolet energy with the upper atmosphere and lower energy visible and infrared light with the lower atmosphere. Conan (Interview #5) thought that x-rays were absorbed by the stratosphere and the lower atmosphere was heated by "ultraviolet and the greenhouse section of it [the atmosphere]." He definitely attributed the greenhouse effect to the lower atmosphere and did not think that greenhouse gases were present in the upper atmosphere.

Returning to Table 3.8, students were also asked what form of energy Earth's atmosphere mainly gives off. Results show that, when circling all the forms of energy that apply for GECI.vA Item 15, pre-instruction students selected ultraviolet most frequently (56%). Several students reasoned that because the atmosphere absorbs ultraviolet from the Sun, it likely gives off ultraviolet as well: "A lot of Earth's energy comes from the Sun which gives off ultraviolet light that goes into the atmosphere and is thus given off by the atmosphere." The next most common pre-instruction response was that the atmosphere mainly radiates infrared energy (46% pre-instruction). Student reasoning behind this selection included the following:

> The atmosphere itself doesn't give off energy unless it is absorbed from the Sun first, but since when the atmosphere is in contact with the rays of the Sun it heats up which is from infrared rays.
>
> The Earth gives off infrared, but it doesn't all make it past the atmosphere because the greenhouse gases absorb some of it.

The item regarding atmospheric radiation was modified on subsequent GECI surveys to allow only one right answer. As a result of this modification, infrared was reported on equal footing with ultraviolet (33% for both) on GECI.vB Item 13. On GECI.vC Item 17, infrared was the most popular pre-instruction selection (37%) and each of the other four distracters were reported at similar frequencies between 14-19%. The difference between these two items are that “x-ray” was replaced with “Earth’s atmosphere does not give off energy” as one of the distracters for GECI.vC Item 17. All post-instruction responses to items on energy radiated by the atmosphere show shifts towards the correct answers of infrared energy (with post-instruction frequencies between 52-68%).

3.5.3 Energy Absorbed and Given Off by Surface

Finally, several survey items were developed regarding the forms of energy absorbed, radiated, and reflected by Earth’s surface. On GECI.vA Item 17, students were allowed to make multiple selections. Students with a strong understanding that Earth surface is mostly heated by visible light from the Sun and infrared energy from the atmosphere could have selected both of these options. Table 3.8 shows this was not the case. Rather, ultraviolet energy was selected on 76% of pre-instruction surveys as primarily heating Earth’s surface. Student reasoning behind this selection were similar to those for heating of Earth’s atmosphere and consistent with student beliefs that ultraviolet is “the strongest light put off by the Sun.” As one student explains, “Ultraviolet light comes from the Sun, and the surface of the Earth is heated primarily by the Sun.” Additionally, students again expressed that ultraviolet energy is higher energy: “I think higher frequency waves have more energy but x-ray is blocked out by the atmosphere." While the majority of students selected ultraviolet alone (46%), the next most popular choice was infrared alone (18%) followed by ultraviolet and infrared together (14%). Infrared and visible were never selected together. Students identifying infrared commonly mentioned that "infrared light is heat." The following explanation shows a student combining both ozone depletion and trapping to select both infrared and ultraviolet:

> Infrared light passes into our atmosphere and gets trapped and continually bounces around absorbing heat and increasing the surface temp. Ultraviolet is the thing that gives people sunburns often without our knowledge.

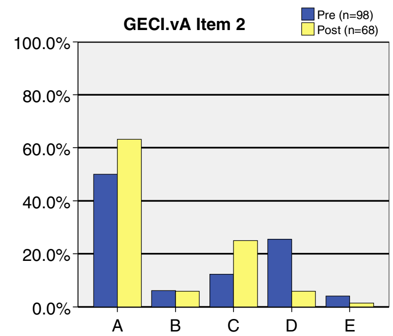
On both a different version of Survey GECI.vA and on later versions of the GECI, similar items regarding the heating of Earth's surface were asked in which students were instructed to select only one option. As Table 3.11 below shows, students were asked to discriminate between the different sources of energy responsible for heating Earth's surface. Because these allowed for only one correct answer, the items were revised to include two forms of energy because the surface is heated by both visible energy from the Sun and infrared from the atmosphere.

Table 3.11 Responses regarding energy heating surface

GECI.vA: Item 2

Which one of the following is most responsible for heating Earth's surface?

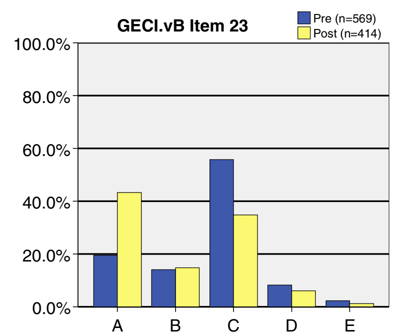
a) Visible light given off by the Sun passing directly through the atmosphere
b) Visible light given off by the atmosphere towards the surface
c) Infrared light given off by the atmosphere towards the surface
d) Ultraviolet light given off by the Sun passing through the ozone hole
e) Heat given off by cars, factories, and other human activities



GECI.vB: Item 23

In addition to visible energy from the Sun, Earth's surface mainly absorbs and is heated by which of the following forms of energy?

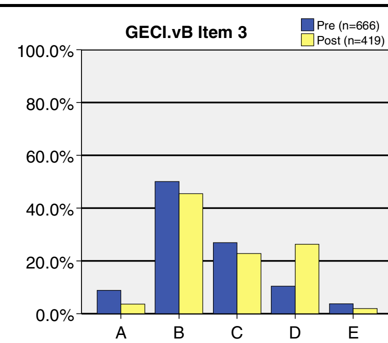
a) infrared given off by the atmosphere
b) ultraviolet given off by the atmosphere
c) ultraviolet passing through the ozone layer
d) infrared given off by cars and industry
e) ultraviolet given off by cars and industry



GECI.vB: Item 3

Earth's surface absorbs and is heated by mainly which two forms of energy?

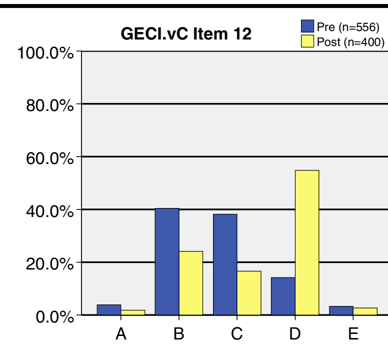
a) ultraviolet and x-ray
b) ultraviolet and infrared
c) visible and ultraviolet
d) infrared and visible
e) radio and infrared



GECI.vC: Item 12

Earth's surface is heated mainly which two forms of energy?

a) ultraviolet and x-ray
b) ultraviolet and infrared
c) visible and ultraviolet
d) infrared and visible
e) radio and infrared



A student predilection towards ultraviolet energy is seen on most all of these items. The majority (56%) of pre-instruction students selected ultraviolet light passing through the ozone hole as heating Earth's surface on GECI.vB Item 23. The two most popular pre-instruction distracters chosen for GECI.vB Item 3 (UV & IR, 50%; VIS & UV, 27%) and GECI.vC Item 12 (UV & IR, 40%; VIS & UV, 36%) both include ultraviolet energy. These results are consistent with students' beliefs regarding the primary type of energy that the Sun is giving off and that the atmosphere is absorbing and/or giving off. In student minds, it seems that the Sun is mostly giving off ultraviolet light and thus the atmosphere and surface are influenced most by ultraviolet light. Significant learning gains were also seen for most all of these items. For GECI.vA Item 17, student responses shifted from surface heating by mostly ultraviolet with some infrared (77%) to mostly visible (73%) and infrared (45%). Each of the GECI.vB and GECI.vC items shown in Table 3.11 also showed post-instruction gains.

Student interviews for GECI.vB Items 3 and 23 shed some light into student thinking about absorption at the surface. Two students, Elizabeth (Interview #9) and George (Interview #6), who selected ultraviolet and infrared from GECI.vB Item 3 associated both of these energies with heat. George further explained that visible light was not the right answer because "visible is more reflective." To eliminate visible energy, he used the correct model that reflective surfaces do not heat up.

For GECI.vB Item 23, two participants expressed difficulties with the idea that the atmosphere could contribute heat to the surface. Kevin (Interview #3) thought that both energy in the atmosphere and heat from cars and factories were more likely to flow out into space rather than heating the surface; energy in the atmosphere “went back into space, not down to Earth.” Rebecca (Interview #2) described a similar model when explaining that heat from the cars and industry would disburse out to heat the surface and then radiate away into space:

> The picture I have in my head is heat would disburse around itself versus, like, so if you had two objects and one was hot, or like a very hot object in a room, then it would eventually cool off and heat up the room a little bit more. But, if the atmosphere is giving off heat, then I would imagine that the Earth is losing heat, and space is getting warmer . . . obviously, not very much [warmer] because it’s large.

Rebecca could not imagine anywhere else heat from the atmosphere could be going other than space. On the other hand, Farah (Interview #8) selected the correct answer that the surface is heated mostly by infrared from the atmosphere, but she admitted that she would have preferred a choice that said the surface is mostly heated by infrared from the Sun. Most importantly, interviews did not reveal student difficulties with interpreting the wording of either GECI.vB Items 3 or 23.

Results from GECI.vA Item 2 are anomalous, however, with visible light from the Sun passing through the atmosphere being more commonly selected (50%) for surface heating than ultraviolet light passing through the ozone hole (26%). Interestingly, many of the student explanations for choosing visible light from the Sun did not explicitly distinguish why Option A was better than Option D involving ultraviolet light. For example, the following quotes explain why students thought the Sun heats the Earth, but not why visible is the more attractive option than ultraviolet:

> The Sun is our main energy source, so it only makes sense that it'd be directly responsible for heating the Earth's surface.
>
> The Sun is our major heat source, without it we would die.
>
> Visible light goes through the atmosphere but so do other types of light and these heat the Earth's surface.
>
> The heat from the Sun gives the Earth's surface the most heat because it is hottest on Earth when it is summer and Earth is tilted toward the Sun in summer.

However, some students explained that they chose visible light based on the belief that more visible light makes it "through the atmosphere" than ultraviolet. As one student put it, "The one with the ozone hole didn't seem right because there was still heat on the Earth before we swiss-cheezed the ozone." Student who did select UV typically described that ultraviolet light was harmful and caused sunburns and skin cancer.

It is also interesting to point out that the correct response to GECI.vA Item 2 is actually Option C, infrared light from the atmosphere. The input of energy due to back-radiation from the atmosphere is actually greater than the amount of energy contributed by visible light passing through the atmosphere from the Sun. This option was selected by 12% of students pre-instruction and 25% post-instruction. It is also noted that following instruction, surface heating by visible energy remained the most popular selection, with the second most popular selection shifting from ultraviolet passing through the ozone to infrared from the atmosphere.

The remaining nine items on Table 3.8 and Table 3.9 deal with student beliefs about energy radiated and reflected by the surface, with some survey versions specifically delineating between daytime and nighttime radiation. On GECI.vA1, student were asked what form of energy the surface "gives off mainly" during the nighttime. A different group of students completed GECI.vA2 which asked the same question but for the daytime. On GECI.vB1, students were asked three items sequentially regarding 1) the form of energy reflected during the daytime, 2) the form of energy radiated during the daytime, and 3) the form of energy radiated during the nighttime. A different group of students completed GECI.vB2, which asked students what forms of energy were mainly reflected and radiated but with no stipulation regarding the time of day. Finally on Survey GECI.vC, students were asked two non-sequential questions regarding the forms of energy radiated during the daytime and nighttime, but they were not asked what form of energy is reflected.

For each of these items, radio and x-ray were selected minimally while the remaining three energies were more common responses. GECI.vA Items 4 and 11 reveal that, pre-instruction, students most frequently selected ultraviolet (55%) and infrared (43%) as being given off during the daytime and infrared (63%) being given off during the nighttime. On GECI.vB when students are prompted to discriminate between reflection and radiation, these results change. On GECI.vB2 Items 29 and 30, which do not deal with the time of day, all three forms of light are popular selections regarding energy reflected by the surface (IR=29%, VIS=20%, UV=31%) while infrared is the clear winner when it comes to radiated energy (IR=38%, VIS=24%, UV=16%). A similar trend holds for GECI.vB1 Items 8-10. For energy radiated at night, infrared was the overwhelming student preference (51%). For energy radiated during the day, infrared was still most popular at 34%; however, ultraviolet (26%) and visible (24%) were more popular than for nighttime radiation. Finally, ultraviolet was the clear choice for energy reflected during the daytime (46%), while visible and infrared were selected at 22% and 21%, respectively. These survey items reveal a trend in student thinking that the surface is mostly giving off or radiating infrared energy, especially at night when there are no forms of energy arriving from the Sun. During the daytime, ultraviolet is the main component being reflected, which follows from the student belief that the Sun mainly gives off ultraviolet energy. Finally, all survey items show substantial post-instruction gains towards infrared as the primary form of energy radiated during both day and night. Less clear gains were found with regards to learning about reflected energy. On GECI.vB Item 29 which did not prompt students regarding the time of day, infrared light became the clear preference post-instruction (43% for IR versus 25% and 23% for VIS and UR, respectively) regarding reflected light. When asked about reflected light during the daytime on GECI.vB Item 8, all three choices were still popular (IR=29%, VIS=35%, UV=29%).

Further insight regarding student reasoning about energy reflected and radiated during the day and nighttime can be gained by looking at written responses and statements during interviews. GECI.vA Items 4 and 11 did not distinguish between radiation and reflection; rather these items asked about forms of energy that the surface "gives off." Because of this, many students did not discriminate between reflection and radiation when interpreting the term "given off." For GECI.vA Item 11, one student described that during the daytime "the Sun gives us ultraviolet and then the Earth gives off infrared" while another student explained "Earth reflects visible light as infrared."

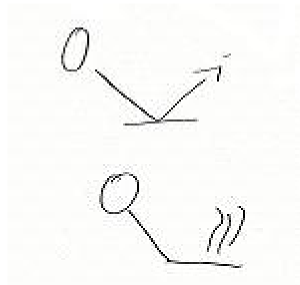
Based upon this observation, subsequent GECI survey items were revised to specify the terms "bouncing (reflecting)" and "gives off (radiates)." However, even after adding these terms, interviews revealed that at least two students, Melissa (Interview #1) and Elizabeth (Interview #9), had trouble distinguishing between these two processes.

Three student interviews revealed interesting student models for radiation and reflection. Conan answered GECI.vB Items 29 and 30 based upon reasoning that the more "wavelike" forms of energy would be more likely to reflect. At first, he thought radio waves were the most wavelike. He later decided that all forms of EM energy are wavelike and "waves have to bounce off something." He ultimately decided that infrared and visible were more likely to reflect because he thought they had longer wavelengths than radio, ultraviolet, and x-ray energies. In Conan's model, longer wavelength light was less likely to penetrate skin and cause cancer, and therefore more likely to reflect.

Paul (Interview #4) interpreted GECI.vB Items 8-10 using the construct that reflected light involved energy that "originated from the Sun" while radiated light originated on Earth, either through "humans, human creations, or heat, infrared radiation given off from the heat of living objects from the planet's core and mantle." These included radio waves, visible light from street lights, fires, and lightning, and infrared energy from "living things that generate heat."

Finally, Kevin (Interview #3) had a solid understanding of reflection, absorption, and radiation, but had interesting ideas about the timing of these processes. When answering GECI.vB Items 29 and 30, Kevin drew the figure below showing energy from the Sun reflecting and radiating off the surface.

Figure 3-1 Student diagram (Kevin, Interview #3)



He clearly described reflected light as a continuous beam that bounces off the surface immediately, shown at the top of the figure. For the bottom of the figure, light was first absorbed by the surface and then radiated some time later by the heated surface. While this student model is close to being scientifically accurate, further probing revealed that in Kevin's model, the surface absorbs energy during the day and radiates energy during the night. He described "it [energy] like gets absorbed during the day and then goes off during night." In Kevin's model, the surface does not radiate energy during the day.

Based upon student difficulties understanding absorption, radiation, and reflection at the surface of the planet, it seems likely that students have an even less clear understanding of these processes in the atmosphere. This is a likely contributor to common student misunderstandings that greenhouse gases reflect energy throughout the atmosphere rather than absorbing and re-emitting energy.

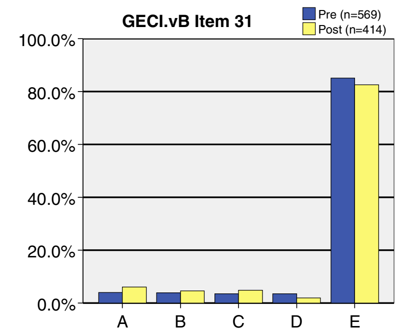
As noted in the paragraph above, Survey GECI.vB2 did not ask student to discriminate between the time of day that the surface radiated and reflected energy. However, the survey did include the following item shown in Table 3.12 intended to determine if students thought the greenhouse effect operated more effectively during a given part of the day or year.

Table 3.12 Responses regarding timing of greenhouse effect (GECI.vB)

GECI.vB: Item 31

The greenhouse effect influences the average global surface temperature

a) only during the day.
b) only during the night.
c) only during winter months.
d) only during summer months.
e) all the time.



Even though pre-instructional responses revealed differences in the type of energy given off by the surface during the daytime and nighttime, the vast majority of students (85%) believe that the greenhouse effect occurs all the time. Because the high frequency of correct pre-instructional responses made it difficult to measure any significant learning gains, this item was removed from the GECI.vC. In addition, student reasoning revealed through interviews for this correct response were not always accurate or complete. Rebecca (Interview #2) explained that it is always daytime somewhere on the planet and the Sun is present year round. Kevin (Interview #3) volunteered a model that the greenhouse effect involves local heating rather than global heating and explained that increasing surface temperatures "probably happens there all the time, but not everywhere all the time." Finally, Conan (Interview #5) felt that the greenhouse effect is most effective "during the latter half of the day and the early part of the night." However, because this wasn't one of the options, he selected the correct Option E – all the time.

Finally, an item was included on GECI.vA (Item 20) and GECI.vB (Item 33) in which students were asked "Greenhouse gases interact most strongly with which of the following forms of energy." In order of preference, students most frequently selected ultraviolet (61% on GECI.vA and 56% on GECI.vB), infrared (52% and 25%), and visible (25% and 12%) pre-instruction. However, student written responses were very vague and confusing, with many students admitting that the selection was a guess. The term "interact" was also vague and could be interpreted in several different manners. Because of this, as well as the large number of questions asking students to identify energies of light already found on the survey, this item was dropped from GECI.vC.

3.5.4 Summary of Insights Regarding Energy

To summarize, an important component of the GECI survey involves student ideas about the types of energy mainly given off by the Sun and absorbed and given off by Earth's atmosphere and surface. The options provided for many of these items were straightforward, listing five forms of electromagnetic radiation. Important trends identified through this line of questioning include the following:

1) Students identify ultraviolet, infrared, and visible energy much more frequently than radio and x-ray.
2) Students believe that the Sun mainly gives off ultraviolet energy. This belief is bolstered both by popular media regarding health risks associated with ultraviolet light as well as classroom curriculum emphasizing that ultraviolet and x-ray light are higher energy and more powerful than other forms of light.
3) The student belief that the Sun mainly gives off ultraviolet energy informs student responses that the atmosphere and surface reflect, absorb, and are heated mainly by ultraviolet energy. This result is consistent with findings that students rarely identify that outgoing terrestrial radiation is different from incoming solar radiation (Dove, 1996; Papadimitriou, 2004; Rebich and Gautier, 2005). This is also an important aspect of student beliefs that the greenhouse effect and increases in surface temperatures are affected by ozone depletion and increased penetration of UV into the atmosphere.
4) Before instruction, students expressed that the atmosphere gives off mostly ultraviolet or infrared energy. Students identified infrared, visible, and ultraviolet energy as being given off by the surface depending upon stipulations about reflection versus radiation of energy and whether it was daytime or nighttime.

5) Students associate ultraviolet energy with sunlight, as shown by the decrease in students selecting ultraviolet energy as an answer related to energy radiated during the nighttime.
6) While the above student beliefs are resistant to change, learning gains were seen with regards to infrared energy being absorbed and given off by the atmosphere and surface. Confusion remained post-instruction with regards to the type of energy mainly reflected by Earth's surface, with more students selecting infrared when the time of day was not stipulated and students split between visible and ultraviolet with regards to reflection during the daytime.

3.6 Energy Balance

As discussed in Chapter 2, students often presented models on SSR surveys that emphasized energy being trapped in Earth's atmosphere but rarely discussed energy leaving to space. Similar findings have been reported in other studies (Fisher, 1998a) This concept was pursued on the GECI Survey through both textual and diagrammatic survey items.

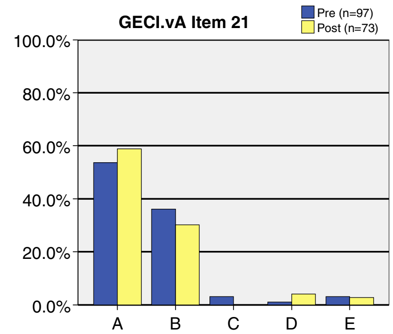
Initial attempts to develop effective wording on survey items related to this concept were met with mixed success. Table 3.13 below shows each of these attempts.

Table 3.13 Responses regarding energy balance (GECI.vA & GECI.vB)

GECI.vA: Item 21

If greenhouse gases were to permanently trap energy in our atmosphere, the temperature of the atmosphere would

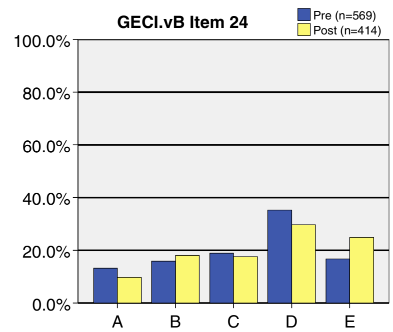
- **a) increase forever.**
- b) eventually stabilize at a higher temperature.
- c) not change.
- d) eventually stabilize at a lower temperature.
- e) decrease forever.



GECI.vB: Item 24

The greenhouse effect influences the flow of energy

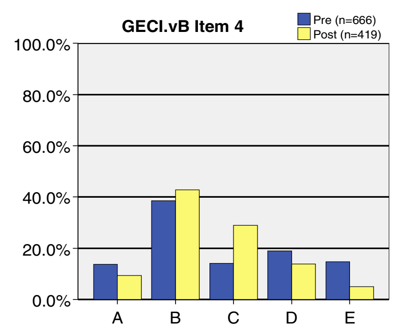
- a) into the Earth system from space.
- b) out of the Earth system into space.
- **c) through the Earth system.**
- d) both A and C.
- e) both B and C.



GECI.vB: Item 4

On average, the total amount of energy leaving the Earth system to space

- a) is greater than the amount of energy arriving from space.
- b) is less than the amount of energy arriving from space.
- **c) is equal to the amount of energy arriving from space.**
- d) depends upon the concentration of greenhouse gases in the atmosphere.
- e) depends upon the status of ozone in the atmosphere.



On GECI.vA Item 21 an attempt was made to test student logic regarding the consequences of permanent trapping of energy in the atmosphere. The survey item shows that over 89% of students surveyed both pre- and post-instruction realized correctly that trapping of energy in the atmosphere will increase the planet temperature

(Options A and B), and a large proportion of these (54% pre- and 59% post-instruction) also recognized that permanent trapping would cause a perpetual increase. As one student described, “It only makes sense that the temp would keep rising.” Students used reasoning regarding energy balance to explain that “more energy would be coming in all the time and not leaving.” However, at least one student used reasoning related to media hype: “That is what the whole global warming issue is about, the increase in the Earth's overall temperature, so I think the increase would be permanent to cause such a big deal.” Even though the question was hypothetical, students selecting Option B had difficulty accepting that the temperature could increase forever. Student invoked explanations involving evaporation of water and circulation of gases and air as mechanisms for stabilization. Others explained, “It would increase till it couldn't any more,” and “I doubt it would increase forever because we'd all eventually die but it would increase so I chose B.” Ultimately, the survey item was removed from subsequent surveys because of the high pre-instruction success rate and the low response frequency for three of the distracters. It is still instructive, however, that student correctly associate trapping of energy with an increase in temperature rather than a decrease. Also, when posed with the scenario of permanent trapping, over half recognize that this would lead to indefinite heating.

Pursuing a different approach, GECI.vB Item 24 asked students about the flow of energy into, out of, and through the Earth system. While pre-instruction responses appeared promising, with a reasonably flat pre-instruction histogram distribution and response frequencies ranging from 13-35%, the post-instruction distribution was almost identical and showed no gain for the correct response (Option C). This result suggested that the distribution was largely due to student guessing, a view confirmed through student interviews. Melissa (Interview #1) expressed confusion about the meaning of the term “Earth system,” and all five students interviewed expressed frustration with the wording of this survey item. The fact that the last two options involved a combination of the first three options was especially confusing for some students (see Interview #5 with Conan). Another student, Kevin (Interview #3), would have preferred an Option F – “all of the above.” Based upon this analysis, the survey item was removed from GECI.vC.

Results from GECI.vB Item 4 were more promising, with a healthy pre-instruction distribution and 39% of the students selecting distracter that the energy leaving to space is less than the energy arriving. The item also showed gains from 14% to 29% for the correct answer that these two quantities were equal. Student interviews confirmed that students did not have difficulty with the wording of the item. Interesting interview discussion regarding this item involved concepts of equilibrium (Interview #4 with Paul) and perfect absorbers (Interview #7 with Raoul). On this item, George (Interview #6) expressed a model similar to the radiation model presented by Kevin (Interview #3) on GECI.vB Item 29-30 (see Section 3.5.3 above):

> [The Earth is] constantly heating up, but it doesn't actually give off heat during the daytime. The only thing it gives off is reflected stuff that you feel as heat, but it's not actually heat from the Earth. It's just heat from the radiation reflecting.

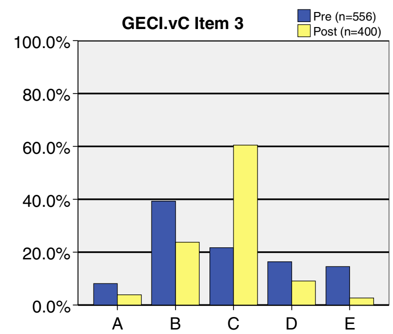
This survey was retained and only slightly modified as GECI.vC Item 3, resulting in a similar pre-instruction distribution and even greater post-instruction gains (from 22% pre- to 56% post-instruction). Table 3.14 below provides the new wording (the word "roughly" was added to Option C). The table also shows GECI.vC Item 18, a third attempt to survey student beliefs about energy balance.

Table 3.14 Responses regarding energy balance (GECI.vC)

<u>GECI.vC: Item 3</u>

On average, the total amount of energy leaving the Earth system to space

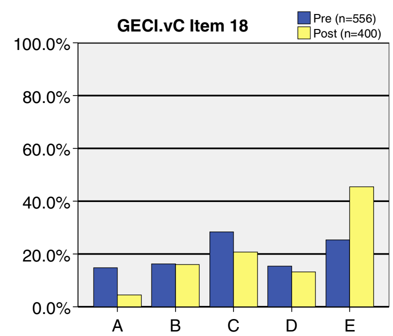
a) is greater than the amount of energy arriving from space.
b) is less than the amount of energy arriving from space.
c) is roughly equal to the amount of energy arriving from space.
d) depends upon the concentration of greenhouse gases in the atmosphere.
e) depends upon the status of ozone in the atmosphere.



<u>GECI.vC: Item 18</u>

Due to the greenhouse effect, Earth's overall surface temperature is affected primarily by

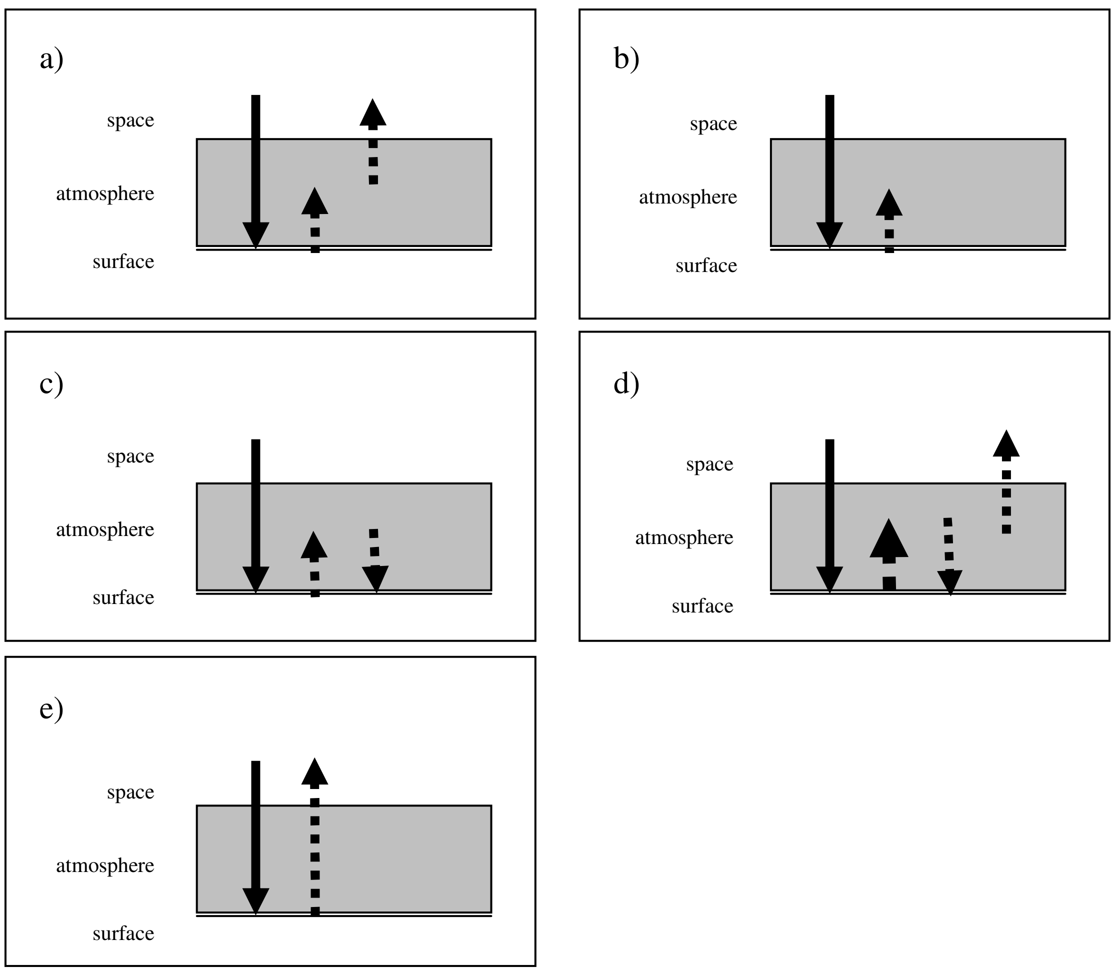
a) an increase in energy entering from space.
b) a decrease in energy leaving to space.
c) both an increase in energy entering from and a decrease in energy leaving to space.
d) energy being permanently trapped in the atmosphere.
e) an increase in the amount of energy absorbed and given off between the surface and atmosphere.



Both of these survey items reveal the pre-instruction belief that energy is somehow trapped by the atmosphere, with less leaving to space than arrives. The pre-instruction histogram for GECI.vC Item 18 is fairly flat, with a slight preference for Option C (28%). This pre-instruction result is consistent with previously discussed findings that students often intermix both ozone depletion (an increase in the amount of energy entering from space) and trapping (decrease in energy leaving to space) (e.g., Papadimitriou, 2004; Rebich and Gautier, 2005). Post-instructional responses for both survey items show learning gains towards the idea of energy equilibrium within the Earth system (GECI.vC Item 3) and between the surface and atmosphere (GECI.vC Item 18).

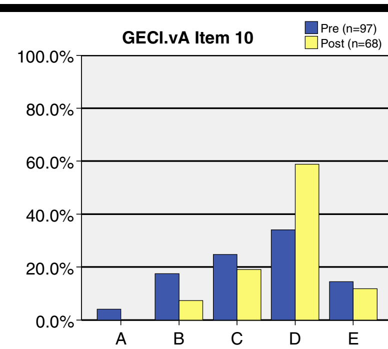
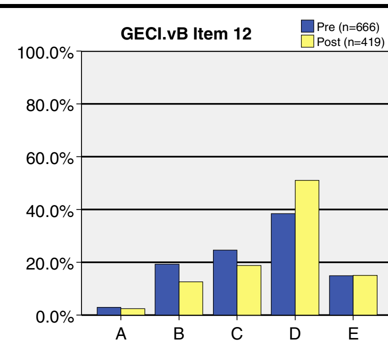
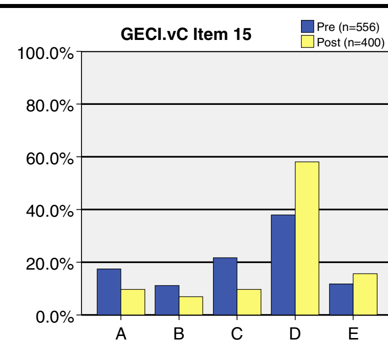
The final attempt at surveying student beliefs about energy balance involved a diagram of energy flow. This survey item proved to be effective in all three survey versions and required only minor modification. Students were provided the diagram shown in Figure 3-2 below, which shows space, Earth's atmosphere, and Earth's surface.

Figure 3-2 Diagram of energy flow on GECI surveys



The caption describing this figure was changed slightly between the three survey versions. In addition, the thickness of the arrows was modified in GECI.vC. In previous versions, all arrows were of uniform thickness. These minor changes were made in response to student supplied responses and student interviews. Student written responses to Options B and E indicated that some student equated the length of the arrow with the amount of energy, which was not the initial intent. Table 3.15 below provides the caption and pre- and post-instructional responses each survey administration.

Table 3.15 Responses regarding energy flow diagram

GECI.vA: Item 10 Each diagram below shows Earth's surface, the atmosphere, and outer space. Select the one answer that best describes how visible light (solid arrow) and infrared light (dashed arrows) are absorbed and given off by each of these three components.	
GECI.vB: Item 12 Each diagram below shows Earth's surface, the atmosphere, and outer space. The solid arrow represents incoming energy from the Sun that is absorbed by the surface. The dashed arrow represents energy that is radiated or given off by the surface. Select the diagram that best represents the transport of both incoming energy from the Sun and radiated energy from the surface.	
GECI.vC: Item 15 Each diagram below shows Earth's surface, the atmosphere, and outer space. The solid arrow represents incoming energy from the Sun that is absorbed by the surface. The dashed arrow represents energy that is radiated or given off by the surface and atmosphere. The thickness of the arrow roughly represents the amount of energy. Select the diagram that best represents the transport of energy.	

In all three surveys, students selected a range of options pre-instruction, although Option A was selected less frequently on GECI.vA (4%) and GECI.vB (3%) and the correct Option D was selected most frequently pre-instruction (34-39%). The survey item was retained because instructional gains were consistently observed for Option D on all survey administrations (with post-instructional frequencies ranging from 51-59%. It is important to note, however, that just because student often selected Option D, they often provided incomplete and incorrect explanations. Some students written responses on Survey GECI.vA described that the light bounced or reflected off the atmosphere or invoked the ozone layer: "The infrared light gets trapped in the ozone layer and bounces back to the Earth and eventually escapes through the ozone." Other student selected the choice because it "looked the coolest."

Student responses for Options B and C on GECI.vA Item 10 reflected student ideas that energy does not always go back out to space. One student selecting Option B described: "I think that infrared doesn't reach space and the visible light obviously comes from space." This sentiment was echoed by another student who explained: "I didn't think the infrared light would reflect back so I didn't chose C or D. I also guessed that it didn't go all the way to space so I didn't guess E." Students selecting Option C predominantly described that the diagram depicted light bouncing in, around, and off the atmosphere and one student even invoked gravity: "Things that go up must come back down."

During interviews covering GECI.vB Item 12, all four of the students correctly chose Option D and interpreted the arrows in the diagram as intended by the survey developers. Similar to Paul (Interview #4), Elizabeth (Interview #9) liked the option best because it showed energy coming in, energy coming up into the atmosphere, and energy bouncing back because of “greenhouse gases that are in the way.” It important to note, however, that Elizabeth and others (see Raoul, Interview #7) describe reflection of light by greenhouse gases rather than absorption and re-emission of energy.

To summarize the survey items discussed in this section, these results support earlier observations that students believe the amount of energy leaving to space tends to be less than the amount of energy arriving from space. Students also have difficulty with terms like “the Earth system” and have difficulty distinguishing and describing between processes occurring at the boundary between the surface and atmosphere and between the atmosphere and space. Finally, even though a student may understand that some energy does go back to space, they do not always have the correct understanding of the interactions that occur within the atmosphere.

3.7 Reflection of Light

As discussed previously, a number of students described trapping models for the greenhouse effect that involved the reflection or bouncing of energy and particles through Earth’s atmosphere, rather than a more accurate description of energy being absorbed by greenhouse gases and then re-emitted in random directions. This was discussed tangentially in both of the previous sections. For example, written explanations and interviews regarding the energy flow diagram shown in Figure 3-2 often described light bouncing around and in the atmosphere.

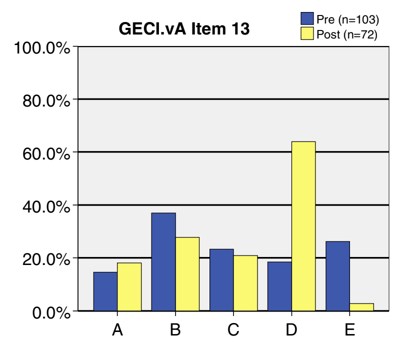
Additional attempts were made in the development of the GECI to address student distinctions between light being reflected versus being absorbed and given off by the surface and the atmosphere. As shown in Table 3.16 below, GECI.vA Items 13 and 19 address this concept specifically. Additionally, these items attempted to distinguish between student beliefs regarding changes in the energy of light through these interactions. Note that students were able to circle all that apply, and that for Item 13 both Option B and D are actually correct responses.

Table 3.16 Responses regarding absorption and reflection (GECI.vA)

<u>GECI.vA: Item 13</u>

Which of the following describes how visible light from the Sun interacts with Earth's surface? Circle all that apply.

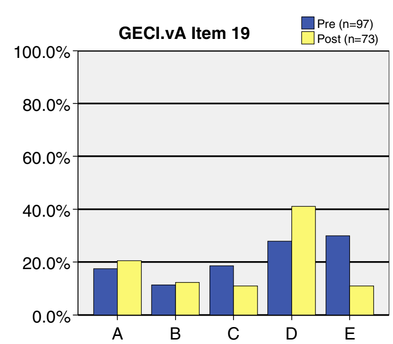
a) Visible light is reflected by the surface as infrared light.
b) Visible light is reflected by the surface as visible light.
c) Visible light is absorbed by the surface which then gives off visible light.
d) Visible light is absorbed by the surface which then gives off infrared light.
e) Visible light is absorbed by the surface which then gives off ultraviolet light.



<u>GECI.vA: Item 19</u>

Which of the following describes how infrared light interacts with greenhouse gases in Earth's atmosphere? Circle all that apply.

f) Infrared light is reflected by greenhouse gases as infrared light.
g) Infrared light is reflected by greenhouse gases as visible light.
h) Infrared light is absorbed by greenhouse gases which then give off visible light.
i) Infrared light is absorbed by greenhouse gases which then give off infrared light.
j) Infrared light is absorbed by greenhouse gases which then give off ultraviolet light.



GECI.vA Item 13 revealed a fairly even distribution of responses pre-instruction, with a slight preference that visible light was reflected as visible light by the surface (37%). Note that one student provided an explanation for Option E that “The Sun gives off ultraviolet light so that is what is in turn given off by the Earth.” This explanation is consistent with findings discussed in Section 3.5 regarding student connections between their understanding of the energy given off by the Sun and given off by the Earth during the daytime. Many of the explanations for Option B, that the visible is reflected as visible, indicated student learning about color and being able to see things because they reflect light. A small fraction (5%) of students selected both of the correct responses, Options B and D. One of these correctly explained: “Visible light is always reflected to some degree which is why we can see things but some of it is also absorbed and turned into heat energy.” However, for the most part, there were lots of varying responses expressing poor discrimination between absorption and reflection and between the different forms of energy.

GECI.vA Item 19 asked students about interactions of infrared light in the atmosphere. This item shows another fairly even distribution of pre-instruction responses, with the most popular responses being that absorbed infrared light is given off as infrared (28%) or ultraviolet (30%). While students often described reflection and bouncing in SSR surveys, students were more inclined to choose that infrared light was absorbed rather than reflected when given a choice. Students who selected the first two options emphasized the importance of bouncing and reflection of energy off greenhouse gases and even mentioned that “infrared bounces off the gasses like a mirror.” For the three options regarding infrared absorption, student explanations varied regarding the various forms of light given off:

> The last 3 are almost identical which made me think there's a higher chance it's one of those so that they could confuse us. I don't think any would give off visible light and it seems pointless to give off light it started with so I chose UV light.

Many of the student explanations indicated guessing on GECI.vA Item 19. One trend that appeared was with students selecting Option E regarding ultraviolet energy. Several students associated the greenhouse effect with ultraviolet energy because both were both bad and dangerous. One student explained: “It makes sense to me because I know UV rays are dangerous, so why else would greenhouse gases be such a big deal.” Another student associated ultraviolet light with sunburns and the greenhouse effect: “The rays that we deal with on a daily basis are ultraviolet. These rays cause sunburns etc.; the greenhouse effect increases these rays.”

It is also interesting to note that that instruction appears to have significantly helped students select Option D for GECI.vA Item 13 that visible light is absorbed by the surface and given off as infrared light. Weaker gains were measured for Item 19 regarding absorption and re-emission of infrared light by greenhouse gases. Since these students received the same instruction, it appears that the concept of light interacting with greenhouse gases was more challenging than light interacting with the surface.

Between Surveys GECI.vB and GECI.vC, two of the items shown on Table 3.8 and Table 3.9 regarding energy reflected off the surface (GECI.vB Items 8 and 29) were dropped in favor of more detailed and context rich survey item shown in Table 3.17.

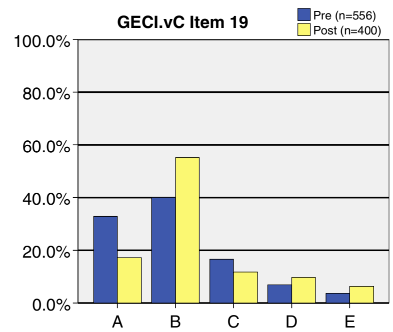
This also decreased the number of items on Survey GECI.vC with options simply involving radio through x-ray light.

Table 3.17 Responses regarding absorption and reflection (GECI.vC)

GECI.vC: Item 19

You walk from a region of shade into a region of direct sunlight and notice you start to feel warmer. Which of the following most correctly describes the cause of the temperature increase?

a) You absorb more ultraviolet energy than you give off (radiate) as visible energy.
b) You absorb more visible energy than you give off (radiate) as infrared energy.
c) You reflect more ultraviolet energy than you give off (radiate) as infrared energy.
d) You reflect more visible energy than you give off (radiate) as infrared energy.
e) You reflect more infrared energy than you give off (radiate) as visible energy.



GECI.vC Item 19 provided more context for students by relating the personal experience of feeling warmer in the sunlight to their conceptual models regarding heating and cooling. Based upon lower pre-instruction responses for the latter three options, many students appear to have a sense that objects are less likely to heat up as a result of reflection of energy. However, pre-instruction results show a roughly even split regarding absorption of ultraviolet and radiation of visible energy (Option A - 34%) versus absorption of visible and radiation of infrared energy (Option B - 39%). This item showed a mild learning gain, with only 19% selecting Option A post-instruction and 52% selecting correct Option B.

3.8 Greenhouse Gases

As discussed in Section 2.8, students identified various gases as being associated with the greenhouse effect on SSR surveys. Input from these surveys was used to develop related items on Survey GECI.vA. Students were given a list of all gases coded from the preliminary survey (SSR.vA) and asked to circle all that apply. Table 3.18 provides a summary of all of the options provided, ranked in order of response frequency.

Table 3.18 Responses regarding specific greenhouse gases (GECI.vA)

Multiple-Choice Option	Number of Students	Percent of Surveys (n=118)
Carbon dioxide (CO_2)	68	69%
Carbon monoxide (CO)	41	42%
Nitrogen (N_2)	33	34%
Oxygen (O_2)	33	34%
Water (H_2O)	33	34%
Ozone (O_3)	30	31%
Methane (CH_4)	29	30%
Chlorofluorocarbons (CFCs)	24	25%
Hydrogen (H_2)	24	25%
Nitrogen oxides (NO_2, N_2O)	24	25%
Smog	22	22%
Sulfur dioxide (SO_2)	18	18%
Helium (He)	16	16%
Smoke particles	16	16%
Freon	15	15%
Ammonia (NH_4)	7	7%

Comparing these results with those from SSR.vC1 in Section 2.8, the same four gases (carbon dioxide, oxygen, nitrogen, and carbon monoxide) are listed in the top four on both surveys. Similar percentages of pre-instruction responses were obtained for carbon dioxide (~70%) and oxygen (~35%) for both surveys. For all other gases, the percentage of responses was higher for the multiple choice survey, which is not surprising given that it is harder to come up with answers from memory. It is possible that carbon monoxide is a popular choice due to student associations with carbon dioxide. It is also likely that students commonly select nitrogen and oxygen due to poor distinction between the two most abundant gases in the atmosphere and greenhouse gases. The large increase in response percentage for water (from 7% on SSR.vC1 to 34% on GECI.vA) and ozone (from 4% to 31%) are also interesting.

Similar to Survey SSR.vC1 discussed in Section 2.2.2 and Section 2.8, students were asked to describe the main characteristics of the greenhouse gases they selected on GECI.vA Item 1. Responses to this open-ended prompt are provided in Table 3.19.

Table 3.19 Characteristics of greenhouse gases (GECI.vA Item 1)

Greenhouse gases:
are found in the upper level of the atmosphere
contain oxygen
absorb different wavelengths of energy
come from plants and photosynthesis
encourage growth
are bad for the environment
make up the atmosphere
hurt the ozone
hurt the Earth
retain heat and provide heat
are produced by humans or things that humans produce
block out UV rays
stay in Earth's atmosphere
are "natural gases in the Earth's atmosphere that trap heat from the Sun and keep it from escaping to space"

Common responses involved ozone depletion and ultraviolet light: "They destroy the ozone so more of the Sun's UV rays pass through the atmosphere." Some students also described greenhouse gases as being bad: "They are bad for the environment, and the greenhouse effect is bad, so it only makes sense that the 'bad' gases would cause a problem." These results are consistent with previously discussed student models for the greenhouse effect.

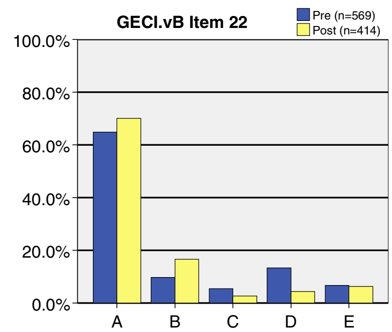
Results from these surveys were used in the development of more traditional multiple-choice items on GECI.vB and GECI.vC surveys. One item asked students to identify the most abundant greenhouse gas. Pre- and post-instruction responses to these questions are shown in Table 3.20.

Table 3.20 Responses regarding most abundant greenhouse gas

<u>GECI.vB: Item 22</u>

Which of the following is the most abundant greenhouse gas?

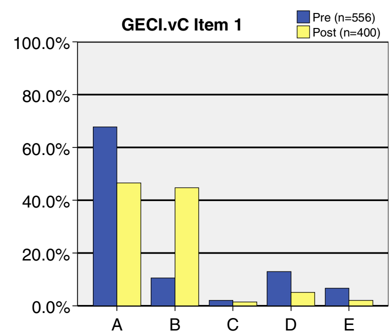
a) carbon dioxide (CO_2)
b) water vapor (H_2O)
c) methane (CH_4)
d) oxygen (O_2)
e) ozone (O_3)



<u>GECI.vC: Item 1</u>

Which of the following is the most <u>abundant</u> <u>greenhouse</u> gas?

a) carbon dioxide (CO_2)
b) water vapor (H_2O)
c) methane (CH_4)
d) oxygen (O_2)
e) ozone (O_3)



Each of the response options was included because of its popularity on the preceding survey studies. Nitrogen was not used based upon the assumption that students would use similar reasoning when selecting oxygen as one of the most abundant gases even though neither are greenhouse gases. Similarly, carbon monoxide was not used because of its assumed associations with carbon dioxide.

Responses reveal the student belief that carbon dioxide is the most significant greenhouse gas before instruction, with 65-66% of students selecting this option on both survey items above. This result is consistent with research efforts by Morgan and Moran (1995), who found that 65% of US undergraduates enrolled in an introductory environmental science course identified that CO_2 is a greenhouse gas on a True/False survey. Higher percentages around 90% were reported for British undergraduates (Spellman et al., 2003) and US pre-service teachers (Khalid, 2003).

After instruction, even more students selected carbon dioxide on GECI.vB. Student interviews revealed that students often overlooked the phrase "most abundant" when answering this question and it was decided that the modifiers "abundant" and "greenhouse" should be underlined on GECI.vC. Interestingly, this did not significantly change in the pre-instructional responses between the two versions. However, there was a significant increase in the percentage of students selecting water vapor post-instruction the underlined version (41%) compared to the item with no underline (17%). It is unclear if this increase was due to the change in the wording of the question, the questions placement in the survey, or variability in the types of classes and interventions included in the two different survey pools.

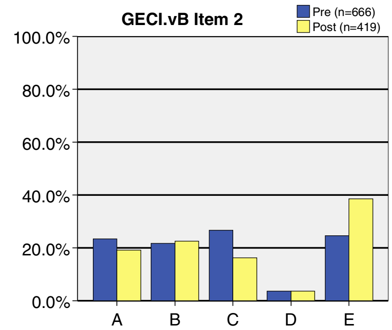
A second GECI item asked students to identify the two most abundant greenhouse gases in Earth's atmosphere (see Table 3.21).

Table 3.21 Responses regarding 2 most abundant greenhouse gases

GECI.vB: Item 2

Which of the following are the most abundant greenhouse gases in Earth's atmosphere?

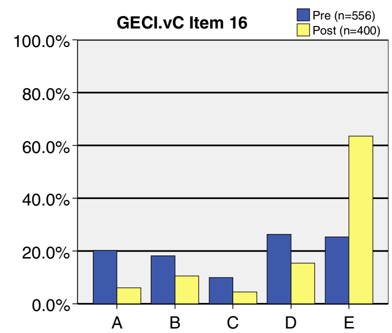
a) carbon dioxide (CO_2) and methane (CH_4)
b) ozone (O_3) and carbon dioxide (CO_2)
c) nitrogen (N_2) and oxygen (O_2)
d) hydrogen (H_2) and helium (He)
e) water vapor (H_2O) and carbon dioxide (CO_2)



GECI.vC: Item 16

Which of the following are the two most <u>abundant</u> <u>greenhouse</u> gases in Earth's atmosphere?

a) carbon dioxide (CO_2) and methane (CH_4)
b) ozone (O_3) and carbon dioxide (CO_2)
c) nitrogen (N_2) and oxygen (O_2)
d) oxygen (O_2) and carbon dioxide (CO_2)
e) water vapor (H_2O) and carbon dioxide (CO_2)



Because carbon dioxide was included in several of the options provided, responses to this item were more evenly distributed then for the previous item. However, very few students (4%) selected the distracter of "hydrogen and helium" (which are the two most abundant gases in the Sun's atmosphere) on GECI.vB Item 2. To improve this question, this distracter was replaced with the option of "oxygen and carbon dioxide," so that four of the five options included carbon dioxide. As with the previously discussed item, the modifiers "abundant" and "greenhouse" were underlined in response to student interviews indicating confusion between the "most abundant greenhouse gases" (correct answer is H_2O and CO_2) and the "most abundant gases" (correct answer involves N_2 and O_2). These changes resulted in a decrease in the number of pre-instruction selections of "nitrogen and oxygen" (from 26% to 11%). Instruction gains were seen with both versions of the item, with 39% and 59% of students selecting water vapor and carbon dioxide post-instruction. Again, it is difficult to distinguish if this was due to changes in underlining on the item, placement in the survey, or administration of the survey.

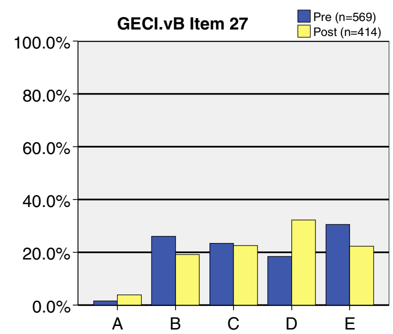
Another GECI item asked students to identify the gas that is not a greenhouse gas. Table 3.22 provides pre- and post-instructional responses to these items.

Table 3.22 Responses regarding non-greenhouse gas

GECI.vB: Item 27

Which one of the following is not a greenhouse gas?

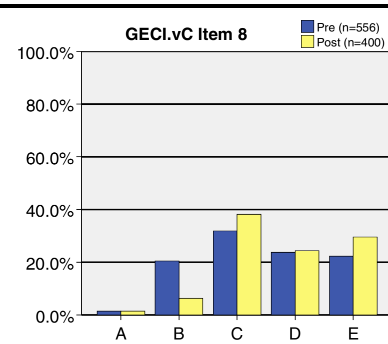
f) carbon dioxide (CO2)
g) water vapor (H2O)
h) methane (CH4)
i) oxygen (O2)
j) ozone (O3)



GECI.vC: Item 8

Which one of the following is not a greenhouse gas?

a) carbon dioxide (CO_2)
b) water vapor (H_2O)
c) methane (CH_4)
d) oxygen (O_2)
e) ozone (O_3)



Carbon dioxide was selected the least on both pre- (<2%) and post-instruction (1-4%) surveys. However, responses for the other four choices were fairly evenly distributed for pre-instructional responses. Interestingly, post-instruction selections of the correct answer of oxygen were higher on GECI.vB Item 27 (32%) than on GECI.vC Item 8 (25%), even though the items were identical and located in similar parts of each survey

(7th and 8th questions in the surveys respectively). These results suggest a difference in the types of classes or interventions involved with the two different survey pools.

In agreement with previous research (Morgan and Moran, 1995; Khalid, 2003; Spellman et al., 2003), the items presented in this section all point to the strong student belief that carbon dioxide is a primary greenhouse gas. Indeed, the most effective item at differentiating student understanding involved student identification of the two most abundant greenhouse gases. Student had more difficulty identifying other less commonly discussed greenhouse gases and appeared to be guessing on GECI.vB Item 27 and GECI.vC Item 8 both before and after instruction.

3.9 Ozone Depletion, Global Warming, and the Greenhouse Effect

As with the results described in Section 2.5 and in the literature (e.g., Francis et al., 1993; Bostrom et al., 1994), students consistently demonstrate confusion and intermixing of concepts from different atmospheric phenomena: greenhouse effect, ozone depletion, global warming, and air pollution. Survey items were developed for the GECI to monitor student distinctions between these processes, with specific attention to comparisons of the greenhouse effect and global warming.

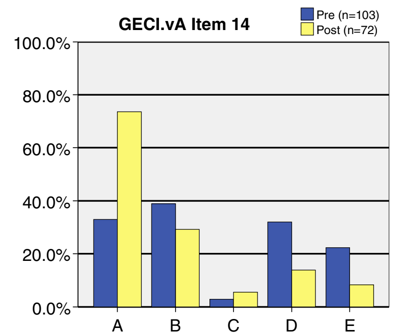
One type survey item asked students to describe associations between human civilization and the greenhouse effect. This question was changed very little between the three versions of the survey (see Table 3.23 below).

Table 3.23 Responses regarding human civilization and greenhouse effect

<u>GECI.vA: Item 14</u>

If humans civilization had never developed on Earth, would there be a greenhouse effect? Circle all that apply.

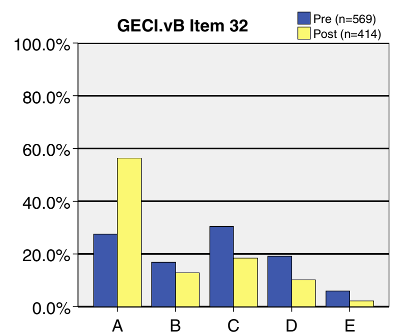
- **a) Yes, the greenhouse effect has always been present in the atmosphere.**
- b) Yes, the greenhouse effect is caused by plants giving off greenhouse gases through photosynthesis.
- c) No, the greenhouse effect is caused by humans breathing out greenhouse gases.
- d) No, the greenhouse effect is caused by humans burning of fossil fuels.
- e) No, the greenhouse effect is caused by humans producing aerosols and refrigerants.



<u>GECI.vB: Item 32</u>

If human civilization had never developed on Earth, would there be a greenhouse effect?

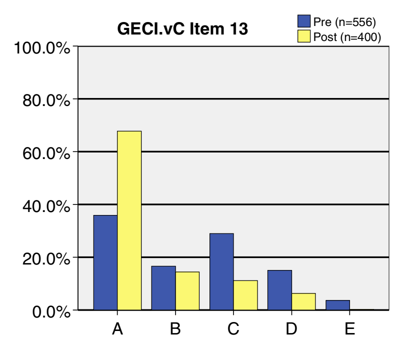
- **a) Yes, the greenhouse effect is caused by naturally occurring gases in the atmosphere.**
- b) Yes, the greenhouse effect is caused by plants giving off gases during photosynthesis.
- c) No, the greenhouse effect is caused by humans burning fossil fuels and releasing pollutants.
- d) No, the greenhouse effect is caused by humans depleting ozone in the atmosphere.
- e) No, there is no conclusive evidence that a greenhouse effect exists.



<u>GECI.vC: Item 13</u>

If human civilization had never developed on Earth, would there be a greenhouse effect?

- **a) Yes, the greenhouse effect is caused by naturally occurring gases in the atmosphere.**
- b) Yes, the greenhouse effect is caused by plants giving off gases during photosynthesis.
- c) No, the greenhouse effect is caused by humans burning fossil fuels and releasing pollutants.
- d) No, the greenhouse effect is caused by humans depleting ozone in the atmosphere.
- e) No, there is no conclusive evidence that a greenhouse effect exists.



GECI.vA Item 14 shows an fairly even pre-instruction distribution for all options except Option C regarding human breathing as the main source of greenhouse gases (3%).

Student who selected both Option B and the correct Option A expressed an understanding that human activities were responsible for accelerating, enhancing, contributing to, and adding to the greenhouse effect. As one student put it, "People have just made it worse." Some of these students also expressed that without a natural greenhouse effect, life as we know it could not have been sustained. Students expressing that the greenhouse effect is a product of civilization (Options C-E) expressed that humans are responsible for pollution, burning of fossil fuels, and production of aerosols. The predominant sentiment from these students was that the greenhouse effect was caused by the release of gases and pollution by humans. "If humans were not here, fossil fuels would not be burned and therefore there would be no greenhouse effect." While not particularly instructive, one particularly anthropocentric student stated, "Because humans cause everything." Student explained they had learned this from environmental groups and because "TV tells me this." From these responses, it appears that the item is successful in distinguishing between students who view the greenhouse effect as a natural process that is enhanced by human activities and students whose understanding of the greenhouse effect is more closely aligned with global warming. Finally, significant gains were observed with this item (from 33% pre- to 74% post-instruction), although it should be noted that a significant fraction of students still identified gases given off by photosynthesis as being responsible for the greenhouse effect post-instruction (29%).

For GECI.vB, the wording of Option A was slightly modified and the distracter of human breathing was replaced with a distracter regarding lack of conclusive evidence for the greenhouse effect. This new distracter was also selected infrequently pre-instruction

(6%). In agreement with other research (e.g., Kempton, 1991; e.g., Gowda et al., 1997; Papadimitriou, 2004), this result indicates that a very low percentage of students do not think the greenhouse effect exists. As Rebecca (Interview #2) described, "I've heard arguments that the greenhouse effect does not actually exist, but I've also heard rumors that Neverland is on the moon, so I'm not sure where that argument stands." Several of the interviewees provided verbal descriptions clarifying that they distinguish between the natural greenhouse effect and the recent enhancement to the greenhouse effect. These students were inclined to selection Option A or B for GECI.vB Item 32. Based upon this analysis, the survey item was unchanged on GECI.vC. Visual inspection of Table 3.23 shows similarities in pre- and post-instruction response frequencies on both survey items. Additionally, strong gains are shown on all three surveys.

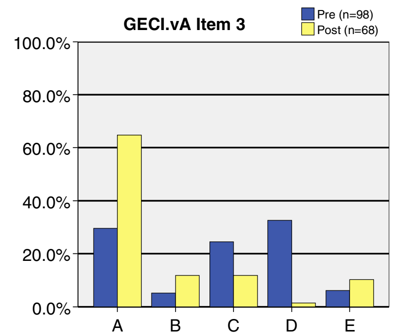
A second attempt to determine student distinctions between the greenhouse effect and global warming are shown on Table 3.24. Here, students were given the same response options, but one stem asked about the greenhouse effect while the other asked about global warming. Due to the manner in which the survey was distributed (see Section 3.1.1) some students had both items on their survey, while students who explained their reasoning answered only one of the items below.

Table 3.24 Responses regarding global warming

<u>GECI.vA: Item 3</u>

The greenhouse effect is

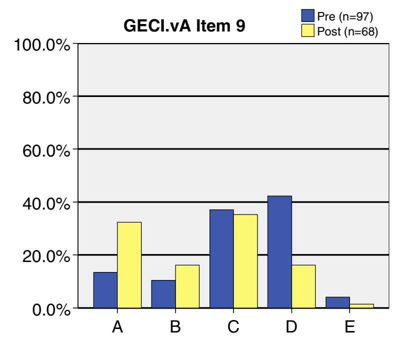
- **a) a phenomenon that has operated in Earth's atmosphere for most of its history.**
- b) a recent phenomenon caused by natural processes.
- c) a recent phenomenon caused by the burning of fossil fuels.
- d) a recent phenomenon caused by destruction of the ozone layer.
- e) none of the above.



<u>GECI.vA: Item 9</u>

Global warming is

- a) a phenomenon that has operated in Earth's atmosphere for most of its history.
- b) a recent phenomenon caused by natural processes.
- **c) a recent phenomenon caused by gases released by burning fossil fuels.**
- d) a recent phenomenon caused by destruction of the ozone layer.
- e) none of the above.



A comparison of pre-instruction results for the two items shows that students tended to associate both recent ozone depletion and burning of fossil fuels with both the greenhouse effect and global warming. There was a slight preference amongst students to identify the greenhouse effect as an old and natural phenomenon. For GECI.vA Item 3, student selecting Option A described that the greenhouse effect was essential for life on the planet. "The greenhouse effect is part of what helped sustain life in the first place." One student even gave the surface temperature of Earth at 280-300 K and explained that temperatures would be much colder without the greenhouse effect. Students selecting Options C and D provided explanations equating the greenhouse effect to global warming: "The greenhouse effect is also called global warming and I remember being told in the late 80s not to use aerosol hairspray because it depletes the ozone and adds to global warming." These students referred to ozone depletion and pollution as being primary causes of the greenhouse effect and obviously conceive of the term greenhouse effect as being global warming.

Similar explanations were provided for Options C and D on Item 9. These students expressed that global warming was the result of pollution, burning of fossil fuels, and destruction of the ozone layer. "Fossil fuels and CFCs that have been most prevalent since the industrial revolution of big countries are a factor that aids with global warming." Another student explained "Gases released by burning fossil fuels has destroyed our ozone layer causing global warming." Explanations from students who selected that global warming was a natural process (either old or recent) were distinctive, though. These students identified global warming with climate change and expressed that climate change has been occurring throughout Earth's history. The following student quotes express this idea:

> The Earth has always cooled and then warmed throughout most of its history ice age.
>
> Since the beginning of Earth the planet has gone through cycles of global warming and cooling, hence the ice ages. However, gases released by burning fossil fuels are also having an effect

Some students who answered GECI.vA Item 3 incorrectly explained that they thought the greenhouse effect was the same thing as global warming. Conversely, some students who answered GECI.vA Item 9 incorrectly explained that global warming is the same as natural climate variation. This important distinction points to the fact that students tend to associate the term greenhouse effect with the enhanced greenhouse effect and global warming rather than the natural greenhouse effect (Dove, 1996; Andersson and Wallin, 2000).

It should also be noted that the histogram for GECI.vA Item 3 shows learning gains towards students correctly describing the greenhouse effect as a natural process. However no learning gains were measured with regards to global warming on GECI.vA Item 9. Rather, students actually shifted from associating global warming and ozone depletion to describing global warming as a natural process.

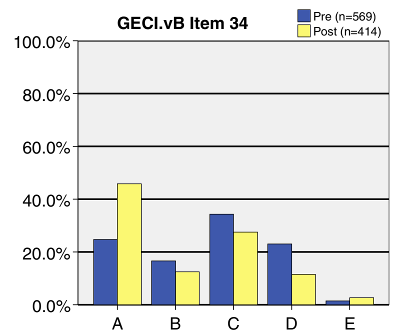
The above items were modified on subsequent survey versions, still with a focus on whether the greenhouse effect was recent or old phenomenon. Table 3.25 shows items that were asked to clarify whether students used the term greenhouse effect to identify a natural process that has operated for most of Earth's history or a recent phenomenon cause by either human activity or natural processes.

Table 3.25 Responses regarding natural and anthropogenic greenhouse effect

<u>GECI.vB: Item 34</u>

The greenhouse effect is

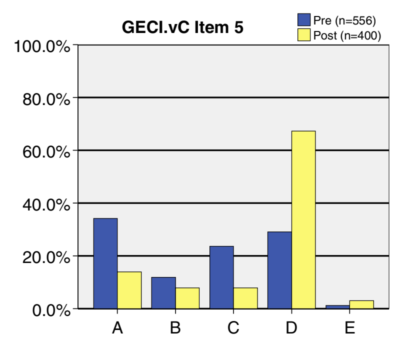
- **a) a process that has operated for most of Earth's history to raise global surface temperature through interactions between gases and various forms of energy**
- b) a process caused by plants that raises global surface temperature and increases humidity, creating conditions similar to those in a plant greenhouse.
- c) a recent increase in the average global surface temperature probably caused by burning of fossil fuels, industry, agriculture, and other human activities.
- d) a recent increase in average global surface temperature probably caused by depletion of the ozone layer which allows more ultraviolet light to reach the Earth's surface.
- e) a recent increase in average global surface temperature probably caused by natural processes including volcanic emission and changes in solar activity.



<u>GECI.vC: Item 5</u>

The greenhouse effect is a very ______ process probably caused by ______.

- a) recent ; burning of fossil fuels, industry, agriculture, and other human activities.
- b) old ; plants that increase humidity and create conditions similar to those in a greenhouse found at a plant nursery.
- c) recent ; depletion of the ozone layer which allows more ultraviolet sunlight to reach the Earth's surface.
- **d) old ; interactions between naturally occurring gases and various forms of energy in the atmosphere.**
- e) recent ; natural processes including volcanic emission and changes in solar activity.



GECI.vC Item 5 is essentially the same question as GECI.vB Item 34. The question has been simplified through the use of underlines for responses in the stem of the question. Note that pre-instruction responses are similar between the two surveys but gains are significantly stronger for GECI.vC Item 5. While this may be due to differences in educational treatments, it is also very possible that the question was easier for students to follow and to answer without guessing when written in the more streamlined format.

Three out of the five students interviewed on GECI.vB Item 34 selected correct Option A. Their rationale for this selection was predominantly due to the emphasis that the greenhouse effect is not a recent phenomenon. Rebecca (Interview #2) would have selected Options C through E (fossil fuels, ozone depletion, and natural processes) had it not been for the term "recent" found in each of these options. Conan (Interview #5) explained selected Option A regarding the greenhouse effect "because it's not a recent thing. I already established to myself that it has always existed, but just exists at a different extent today." While students did not express difficulty with the survey item, the did comment on the length of the item and that it took a long time to read. This was a primary motivation for changing the wording structure of the item on GECI.vC Item 5.

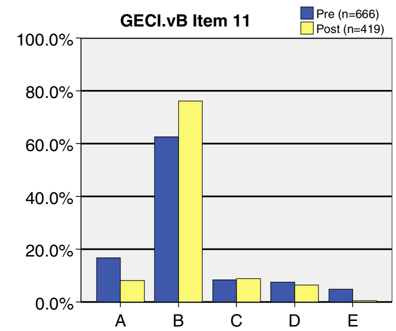
Another attempt regarding the natural and enhanced greenhouse effect was asked through GECI.vB Item 11 shown below.

Table 3.26 Responses regarding greenhouse effect and recent human activity

<u>GECI.vB: Item 11</u>

Which of the following most accurately describes the relationship between the greenhouse effect and recent human activity?

a) Recent human activity is responsible for the creation of the greenhouse effect.
b) The greenhouse effect has operated for most of Earth's history, but recent human activity appears to be enhancing the greenhouse effect.
c) The greenhouse effect has operated for most of Earth's history, and recent human activity has had almost no influence on the greenhouse effect.
d) The greenhouse effect has operated for most of Earth's history, but recent human activity appears to be decreasing the greenhouse effect.
e) Recent human activity has stopped the greenhouse effect all together.



Far and away the most popular response to the above item is that the greenhouse effect has operated for a long time and that human activity is enhancing it. This was selected by 63% of the students pre-instruction and 76% post-instruction. One interpretation of this result is that students do distinguish between a natural and enhanced greenhouse effect if presented in the proper manner. However, Interview #6 with George revealed an alternative explanation. George answered the item correctly, but his explanation was based on the idea that climate change has occurred throughout history and humans have recently enhanced climate change. Nowhere in his description is a model of increased background temperatures due to a natural greenhouse effect. For George, the greenhouse effect is equivalent to climate change. Due to concerns like this from the interviews as well as the skewed pre-instruction response frequency distribution, this survey item was dropped form Survey GECI.vC.

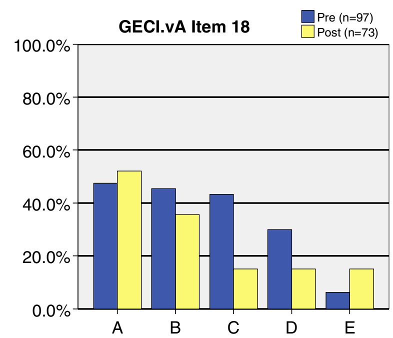
Finally, students were asked to describe the causal relationships between the greenhouse effect, global warming, and ozone depletion through survey items shown in Table 3.27.

Table 3.27 Responses regarding links between GHE, GW, and ozone depletion

<u>GECI.vA: Item 18</u>

Which of the following describes the cause(s) of global warming? Circle all that apply.

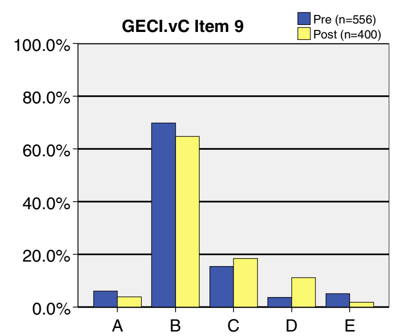
a) Increase of the greenhouse effect causes global warming.
b) Decrease of ozone causes global warming.
c) Increase of the greenhouse effect causes decrease of ozone which causes global warming.
d) Decrease of ozone causes increase of the greenhouse effect which causes global warming.
e) None of the above.



<u>GECI.vC: Item 9</u>

Which of the following best describes the relationship between the greenhouse effect and global warming?

a) The greenhouse effect and global warming are the same thing.
b) An increase in the greenhouse effect may be causing global warming.
c) Global warming may be causing an increase in the greenhouse effect.
d) The greenhouse effect and global warming are likely unrelated.
e) There is no definite proof that either the greenhouse effect or global warming exists.



GECI.vA Item 18 asked students to assign causality between the greenhouse effect, global warming, and ozone depletion. Note that very few pre-instruction students (6%) selected Option E – none of the above – and that the response frequencies for each of the remaining options are very high because students could circle all answers that apply. However, following instruction, very little gain is seen towards the correct Option A (from 47% to 52%) and all three of the other distracter responses decreased. This seems to indicate that less student learning occurred about what global warming than about what global warming is not. Student explanations reveal that students commonly associate global warming with pollution, burning fossil fuels, and ozone depletion.

This item was revised into GECI.vC Item 9, with students being asked explicitly to describe the relationship between the greenhouse effect and global warming. Note here that the option regarding ozone depletion has been removed. This change significantly shifted student pre- and post-instruction responses toward the correct response that global warming may be caused by an increase in the greenhouse effect (66-67%). However, the item also shows very little change following instruction. It is unclear if this was due to weaknesses in the learning interventions or in the survey item.

3.10 Causes of the Greenhouse Effect

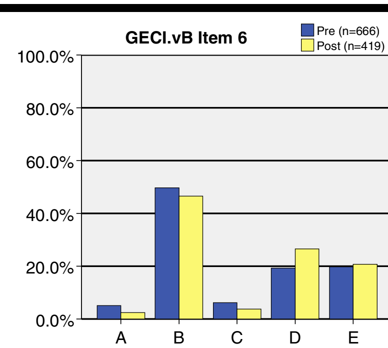
Only one attempt was made on a GECI survey to address anthropogenic sources of greenhouse gases in the atmosphere. GECI.vB Item 6, shown below, provided five options.

Table 3.28 Responses regarding anthropogenic sources of greenhouse gases

GECI.vB: Item 6

Which of the following does not increase the amount of greenhouse gases in the atmosphere?

a) burning of fossil fuels in automobiles
b) certain agricultural activities including growing rice and raising cattle
c) cutting down and burning trees in rain forests
d) operation of nuclear power plants
e) use of synthetic and manure fertilizers



Student interviews indicate that “agricultural activities” was the most popular choice (50% pre- and 47% post-instruction) because it seemed like it was the least damaging to the environment. One of the students, George (Interview #6), selected Option B because he couldn’t see why growing rice and raising cattle would be bad for the atmosphere. Each of the other options was either “no good” for the environment and atmosphere. Even though he recognized that nuclear power plants are fairly clean and that water for cooling the uranium core was not a problem, he mentioned public fears of radiation, stating “I’m sure the radiation and whatnot that comes from it doesn’t help.”

The item was removed from GECI.vC for two reasons. First, as mentioned in Chapter 1, previous research already focuses more closely on environmental aspects of human enhancement of the greenhouse effect. The GECI instrument was designed to focus on student models regarding the physical mechanism of the greenhouse effect. Second, it was realized during data analysis that none of the answers on GECI.vB Item 6 is technically correct. The best choice involves operation of nuclear power plants because it does not involve the burning of fossil fuels. However, the process does release steam into the atmosphere, which is a greenhouse gas.

3.11 Consequences of the Greenhouse Effect

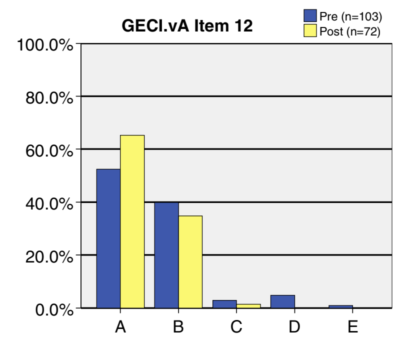
During the development process of the GECI survey, one aspect of the consequences of the greenhouse effect was pursued. Again, literature in the field already extensively deals with consequences of an enhanced greenhouse effect (see Section 1.4). The only effort that was made here was to quantify the frequency of the student belief that the greenhouse effect causes increased surface temperatures. The survey items shown in Table 3.29 were administered on Surveys GECI.vA and GECI.vB.

Table 3.29 Responses regarding influence of greenhouse effect on temperature

GECI.vA: Item 12

Earth's overall surface temperature is

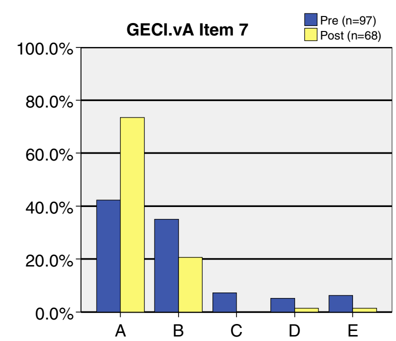
- **a) warmer than it would be without greenhouse gases.**
- b) cooler than it would be without greenhouse gases.
- c) the same temperature as it would be without greenhouse gases.
- d) has not yet been accurately measured.



GECI.vA: Item 7

Which of the following is true about the greenhouse effect and liquid water on Earth?

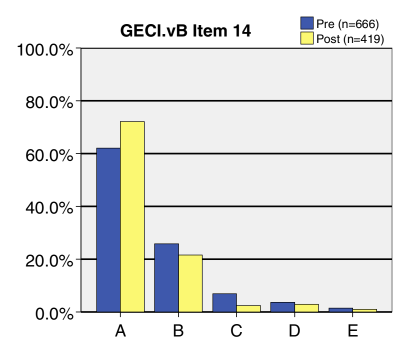
- **a) The greenhouse effect warms the planet enough for water to be a liquid on Earth.**
- b) The greenhouse effect warms the planet, but not enough to affect whether water can be a liquid on Earth.
- c) The greenhouse effect cools the planet enough for water to be a liquid on Earth.
- d) The greenhouse effect cools the planet, but not enough to affect whether water can be a liquid on Earth.
- e) The greenhouse effect does not change the temperature of the planet.



GECI.vB: Item 14

Due to the greenhouse effect, Earth's overall surface temperature is

- **a) warmer than otherwise because energy is temporarily trapped in the atmosphere.**
- b) warmer than otherwise because energy is permanently trapped in the atmosphere.
- c) cooler than otherwise because less energy gets into the atmosphere.
- d) cooler than otherwise because energy leaves the atmosphere more quickly.
- e) the same temperature as it would be without a greenhouse effect.



Surprisingly, GECI.vA Item 12 shows a high number of responses favoring that the greenhouse effect cools the planet (40% pre- and 35% post-instruction). This result conflicted with finding in the literature (Boyes and Stanisstreet, 1992; Boyes and Stanisstreet, 1993; Groves and Pugh, 1999) and from SSR.vA. However, an analysis of student reasoning showed that many student simply misinterpreted the question. Eight out of the thirteen students who provided explanations for Option B on this item indicated in their responses that the greenhouse effect makes the planet warmer, not cooler. For example, the following student selected that the surface is cooler than it would be without greenhouse gases, but explained "Without the greenhouse effect, the Earth would be cooler because the greenhouse effect warms the Earth." Only 7% of student explanations provided legitimate explanations revealing that they actually thought the greenhouse effect cools the planet by blocking UV rays and preventing heat from reaching the surface. It is apparent that the wording of the survey item was confusing to several students. By and large, students who selected both Option A and B described that the greenhouse effect makes the planet warmer by trapping energy and heat.

GECI.vA Item 7 more effectively determined that over 80% of students associated the greenhouse effect with warming. This was confirmed through the administration of GECI.vB Item 14. Here, 88% of students pre-instruction and 94% post-instruction identify that the greenhouse effect increases the overall surface temperature of Earth (Options A and B combined). Additionally, Option A regarding temporary trapping is selected ~3 times more frequently than Option B regarding permanent trapping. It is obvious from this survey item that students associate increased temperatures with the greenhouse effect. Student interviews revealed that it was harder to conceptualize permanent trapping than temporary trapping. Elizabeth (Interview #9) stated, "I'm sure some of it still makes it out or else we'd be getting warmer and warmer and warmer, but we're getting slowly warmer." Paul (Interview #4) did not "think that it can be permanently trapped. I think that's pretty impossible." This survey item was removed from GECI.vC because the high frequency of correct responses pre-instruction did make the item particularly discriminating. It also appeared evident that students tended to associate the greenhouse effect with warming more than cooling and unnecessary to survey this student belief further.

3.12 Summary of Insights from GECI Development

This chapter has provided a detailed summary of the development process of the Greenhouse Effect Concept Inventory. This instrument was developed and tested over the course of three semesters. The initial survey, GECI.vA, was informed through coding of SSR surveys discussed in Chapter 2. This survey involved 21 survey items administered using 6 different versions to allow the collection of student explanations of reasoning for each item. Analysis of pre- and post-instruction response frequencies and student responses were used to develop two version of Survey GECI.vB. Each of these consisted of 14 survey items on similar content topics but with slightly different wording. Interviews were conducted with 9 student volunteers to identify any survey items that students were likely misinterpreting. Interview results and response frequency distributions were used to develop GECI.vC, a 20 item instrument. The primary focus of this concept inventory is to assess student understanding before and after instruction on physical mechanisms and characteristics associated with the natural greenhouse effect.

Each of these survey instruments provided insight into student thinking on this topic. One of the most significant results was identification of a strongly held belief that the Sun mostly radiates ultraviolet energy, a response that was selected by roughly 60-80% of students on all surveys before instruction. This belief is reinforced both by risks associated with skin cancer and classroom discussions of the EM spectrum. While previous research has recognized student associations between ultraviolet energy and heat, this is the first report regarding the strong belief that the Sun is mostly radiating ultraviolet energy. It was also found that this belief impacted student understanding of the types of energy absorbed and given off by both the atmosphere and surface of Earth. Ultraviolet energy was the predominant choice for heating the atmosphere and heating the surface during the day, while infrared was the most popular choice for energy given off during the night. Interviews uncovered that students think the surface absorbs energy during the daytime and radiates energy only during the night. Students also had poorly defined understandings of reflection compared with the absorption and emission of light (both at the surface and within the atmosphere).

Student models involving ozone depletion and trapping of both energy and pollution were confirmed through GECI survey items that described various student models identified from the SSR surveys. The concept of energy balance was also pursued. Students generally thought that less energy leaves to space than arrives. When posed with the model of permanent trapping of energy, many students recognized that this would lead to indefinite increases in temperature. The majority of students recognized that the greenhouse effect leads to increased surface temperatures.

Carbon dioxide was identified as the most abundant greenhouse gas by over roughly 65% of students before instruction, a result that agrees almost exactly with a previous study of US undergraduates by Morgan and Moran (1995). The other contenders for greenhouse gases included carbon monoxide, nitrogen, and oxygen.

Finally, student responses indicated pre-instruction ambivalence over the distinction between the greenhouse effect and global warming, although two survey items (GECI.vB Item 11 and GECI.vC Item 9) indicate beliefs that recent human activity is enhancing the greenhouse effect and that this may be causing global warming. However, some students associate the greenhouse effect with climate change rather than with a natural increase in background global temperatures. The GECI.vC survey instrument does not deal substantially with the causes and consequences of an enhanced greenhouse effect. Rather, it targets student understanding of the physical mechanisms for the natural greenhouse effect, the types of energy involved, and the concept of energy balance.

Several modifications were made to survey items over the development process. This included revisions of formatting and wording, swapping of various response options and stems, and addition and removal of some survey items. While this chapter has focused more on an item-by-item analysis of the evolution of survey, Chapter 4 presents a validation study of the GECI.vC survey instrument, along with a description of the use of this instrument in a preliminary study involving specific educational interventions focused on improving students understanding of the greenhouse effect.

CHAPTER 4: VALIDATION OF GECI.VC AND TESTING OF A LECTURE TUTORIAL ACTIVITY

4.1 Overview

A key outcome of this study is the development of the Greenhouse Effect Concept Inventory (GECI). This survey instrument is a quantitative instrument that can be used to assess learning gains on key greenhouse effect concepts about which students tend to have inaccurate beliefs and reasoning difficulties. As described in the previous chapters, this instrument was developed through an iterative process involving Student-Supplied Response (SSR) surveys, and different versions of the GECI which included both Multiple Choice (MC) and Multiple Choice with Explanation of Reasoning (MCER) survey items. Through this process, a number of recurring student beliefs and reasoning difficulties were identified and have been discussed at length in the preceding chapters.

This chapter addresses validation of the GECI.vC survey items and further development of the survey as a whole. A preliminary investigation using the instrument to differentiate between different classroom interventions related to the greenhouse effect is also presented. The chapter also describes several metrics that were used to validate the survey instrument and an expert review involving specialists in planetary science. Finally, recommendations regarding future use of the GECI are provided.

4.2 Description of GECI.vC Instrument

The third version of the Greenhouse Effect Concept Inventory (GECI.vC) consisted of 20 content items and 6 background items. Each of the items was multiple-choice and typically employed 5 response options. The survey was limited to this length so that it could be completed within a 15 minute timeframe without significantly interfering with normal classroom procedures and activities associated with the undergraduate classes to which it is administered.

The content items found on the GECI.vC survey can be grouped into five thematic categories. Each of these is listed below in Table 4.1 along with a description of which survey items addressed each theme. Each theme is evaluated through use of several survey items to ensure multiple sampling attempts for each concept. A complete version of the survey as it was administered is found in Appendix A.

Table 4.1 Thematic categories for GECI.vC survey items

Theme	Item	Description
GHG – Types of greenhouse gases	1	H_2O is the most abundant greenhouse gas
	8	O_2 is not a greenhouse gas
	16	H_2O and CO_2 are two most abundant greenhouse gases
EM – Types of electromagnetic energy associated with Sun, atmosphere, and surface	10	Sun mainly radiates visible and infrared energy
	14	Sun radiates visible energy at maximum intensity
	2	Atmosphere mainly absorbs and is heated by infrared
	17	Atmosphere mainly radiates infrared
	12	Surface is heated mainly by infrared and visible
	6	During nighttime, surface mainly radiates infrared
	20	During daytime, surface mainly radiates infrared
EQ – Energy equilibrium and balance	3	Energy leaving Earth equals energy arriving from space
	15	Energy flow diagram of solar and terrestrial radiation
	18	Energy exchange between surface and atmosphere
	19	Surface absorbs visible and radiates infrared
MECH – Greenhouse effect mechanisms	4	Greenhouse gases transparent to some but not all energy
	7	GHE influences flow of energy through atmosphere
	11	Greenhouse gases absorb and give off specific energies
GW – Global warming vs. greenhouse effect	5	GHE is old process involving gases and forms of energy
	9	Increase in GHE may be causing global warming
	13	GHE occurs naturally even without human civilization

The first theme listed in Table 4.1 addressed student beliefs regarding the primary greenhouse gases through three survey items. These items (which involve knowing that water and carbon dioxide are abundant greenhouse gases and oxygen is not a greenhouse gas) are perhaps the simplest and most knowledge-based items found on the instrument. The second theme involves set of seven items addressing the forms of energy that are radiated by the Sun and absorbed and radiated by the atmosphere and surface. These response options for these items (i.e., five forms of electromagnetic energy) appear on the surface to be simplistic knowledge questions. However, a complete understanding of the greenhouse effect is required in order to answer any and all of these items correctly. The third category involves student understanding of energy flow through the atmosphere and the concept that the Earth system is in energy balance or equilibrium; this category consists of 4 items. Three items address student big-picture models of how the greenhouse effect works; these items are more context rich than the other items on the survey. Finally, the last category involves three items to determine student discrimination between the greenhouse effect and global warming. Based upon student confusion between the greenhouse effect and global warming, one might argue that the instrument should define the difference between these two phenomena for students from the outset to avoid misevaluating student understanding on the remainder of the survey. However, providing the definitions of these would subvert the fundamental purpose of the instrument, to elicit student beliefs regarding these phenomena and discriminate changes in understanding as a result of instruction.

4.3 Research Design for Instructional Intervention Study

Six undergraduate classes participated in the administration of Survey GECI.vC during the Spring 2006 semester. Two of these were sections of the same astronomy class taught by the same instructor, two were sections of the same atmospheric science class taught by the same instructor, and two were different planetary science classes taught by two different instructors. Results from this administration are a key component of the survey validation analysis described below. In addition, the survey was used as an research instrument as part of a preliminary controlled intervention study involving the astronomy and atmospheric science classes described above. Time and logistical constraints did not allow for a controlled intervention study with the two planetary science classes, both of which treated the greenhouse effect with 1-2 traditional lectures and a homework assignment.

The intervention study in the astronomy and atmospheric science classes involved the use of a Lecture Tutorial (LT) activity focused on the greenhouse effect and the flow of energy through Earth's atmosphere. This Socratic-dialogue inducing style in-class activity was developed as one attempt to confront several student naïve beliefs and reasoning difficulties described in the previous chapters. Specifically, the LT confronted student understanding of the type of energy radiated by the Sun, radiated by Earth's surface, and absorbed by greenhouse gases in the atmosphere. The activity also addressed the concept of energy balance, the flow of energy through the atmosphere, and increased surface temperatures resulting from the nature of this energy flow. A copy of the LT is provided in Appendix L. The effectiveness of this LT was tested through educational interventions involving the astronomy and atmospheric science classes. The details of these interventions, which varied between these two classes, are described below.

With the atmospheric science classes, one section met three time a week (MWF) for 50 minutes each; the other section met twice a week (TR) for 75 minutes each. Students in both sections completed the GECI.vC one week prior to instruction on the greenhouse effect. Apart from breaking up the lecture into different segments based upon the variation in class length, the professor provided identical lectures with demonstrations related to the greenhouse effect in both sections. In the MWF class, this set of lectures spanned 3 class periods for a total of 150 minutes of instruction. For the TR class, the professor covered the same material over the course of 2 class periods for a total of 150 minutes. The content of these lectures covered the electromagnetic spectrum, Wien's Law and Stephan Boltzmann Law using a demonstration with a light bulb and dimmer switch, energy balance using cartoon diagrams, the absorption properties of greenhouse gases, and a discussion and diagrams of the greenhouse effect process. At this point, the TR class, hereafter referred to as "ATMO-Lecture," moved on to an unrelated lecture on seasons and was never given a copy of the LT activity described above. Meanwhile, the MWF class was given an additional 50-minute class period to complete the LT activity in small groups. Only about half of the students in this intervention section volunteered to stay in class to complete the LT. This group of students has been labeled "ATMO-Lecture+LTA" to indicate that they completed the Lecture Tutorial Activity in class. The remainder of the students departed from the MWF class with the LT handout in hand, an unfortunate consequence of the fact that the LT was stapled to the human subjects consent form that was passed out at the beginning of the period. It is not known with confidence whether students in this group completed the LT outside of class, but this is a possibility. This third group has been labeled "ATMO-Lecture+LTH" to indicate that the group received the handout but may or may not have studied the activity outside of class. Due to scheduling constraints, the post-instruction survey was administered one month following the completion of instruction on the greenhouse effect. During the intervening time, students in the class spent ~2.5 hours covering seasons, took an hour long quiz which included the topic of the greenhouse effect, enjoyed spring break, and spent ~2.5 hours on humidity and clouds. Pre- and post-instruction results discussed below were used to compare the three groups (ATMO-Lecture, ATMO-Lecture+LTH, ATMO-Lecture+LTA) to determine if the addition of the LT had an impact on student understanding of the greenhouse effect as measured by the GECI.vC.

In the astronomy classes, an intervention involving the LT was also conducted but with a slightly different research focus. While the ATMO-Lecture+LTA group described above received an additional 50 minutes of class-time on the greenhouse effect compared to ATMO-Lecture, an attempt was made in the astronomy class to spend equal class-time on the greenhouse effect. To this end, while one section worked on central ideas of the LT in small groups during class, the second section received a narrative provided by the instructor on the LT described below. Both sections met twice a week (TR) for 75 minutes, and the classes were taught back-to-back from 11AM-12:15PM and from

12:30PM-1:45PM. One week prior to instruction, students from each class completed GECI.vC. The greenhouse effect was then covered over the course of only one class period. Both sections first received an identical mini-lecture regarding the greenhouse effect. This took 22 minutes in the first section and 27 minutes in the second because more student asked questions in the latter section. The first section then spent 22 minutes completing the LT activity in small groups followed by a 7 minute debrief with the instructor highlighting the major points of the activity. This treatment group is labeled "ASTR-Lecture+LTA." The second section did not complete the LT as a small group activity; rather, the instructor spent the next 16 minutes going over the LT activity in a lecture narrative format. During the narrative, the instructor verbally discussed each question on the LT activity along with an explanation of both correct responses and commonly held misconceptions for each answer. These questions and answers were presented in a one-way rhetorical format in which student interactions and feedback were not elicited. At relevant times, each of the figures found on the LT activity was shown to the class on a projection screen and discussed in detail. The instructor intentionally decreased the amount of wait time that would normally be used during question-based instruction and did not allow students to discuss or respond to the questions. Rather, after reading each item, the instructor provided an answer and moved on. This group of students is labeled "ASTR-Lecture+LTN" to indicate that this group received the LT as a "Lecture Tutorial Narrative." Following the LTA and LTN interventions, the instructor concluded each class with a ~10 minute discussion distinguishing between the greenhouse effect and global warming. Table 4.2 below provides a summary of this timeline.

Table 4.2 Timeline of interventions in astronomy sections

ASTR-Lecture+LTA	Minutes	ASTR-Lecture+LTN	Minutes
GHE Lecture	22	GHE Lecture	27
LT Activity	22	---	---
LT Debrief	7	LT Narrative	16
GHE versus GW	8	GHE versus GW	9
Total Time	59	Total Time	52

As the table shows, a strong effort was made to spend equal instructional time in both sections. Also, both classes received the same content on the greenhouse effect, including a Lecture Tutorial that was developed to confront specific misconceptions commonly held by students. The only difference between these groups was that one group did the LT as an activity in collaborative groups (ASTR-Lecture+LTA) while the second group received instruction on the lecture tutorial through a detailed narrative delivered by the instructor (ASTR-Lecture+LTN). As discussed in Section 4.7, however, it is important to note that this latter treatment was not a traditional lecture but rather the delivery of a Lecture Tutorial in a narrative mode that still directly confronted commonly held misconceptions. Finally, through attendance records it was possible to track which students were present for each of these interventions and those students who were not in class to receive treatment. This group is labeled “ASTR-Absent.”

Two research questions were studied through this intervention: 1) Did either intervention involving the LT have a measurable impact on student understanding of the greenhouse effect? 2) Was there a measurable difference in learning gains between students who completed the LT activity in small groups versus those who received the Lecture Tutorial Narrative? Unlike the atmospheric science classes, the post-instruction survey was administered at the start of the class immediately following the intervention.

4.4 Data Cleaning and Analysis Considerations

During Spring 2006, a total of 577 students completed GECI.vC prior to instruction on the topic of the greenhouse effect. Following instruction, the same survey was administered to and completed by 415 students. This data, which was collected using Pearson Mark Reflex scantron forms, was scanned into an SPSS file and subsequently cleaned and analyzed. Table 4.3 provides a summary of the number of students remaining in the dataset as a result of various data cleaning steps described after the table.

Table 4.3 Number of cases following cleaning of GECI.vC surveys

	Pre-Instruction	Post-Instruction
Total surveys collected	577	415
Cleaned cases (completely and accurately bubbled)	556	400
Cleaned matches	332	332
Cleaned matches with post-instruction Item 25 ≠ “A”	273	273

To clean the dataset, all incomplete and inaccurately bubbled surveys were flagged. Student who left more than two items blank on the survey (including both content and background items) were removed from the dataset on the basis that these students may have been rushed for time or did not complete the GECI survey seriously. Additionally, three of the content items (Items 21, 25, and 26) provided less than five options. Student who bubbled in an invalid option (e.g., Option E) on the SCANTRON for any of these three items were also removed based upon the possibility that this may have resulted from the student who randomly bubbled without reading the survey items. This cleaning process removed roughly 4% of the surveys from the dataset, resulting in 556 pre- and 400 post-instruction surveys. All 956 of these surveys were used in the analyses presented in Chapter 3 to compare changes in the response frequency distribution following instruction. However, a more robust and conservative analysis can be conducted by analyzing only matched surveys. Pre- and post-instruction matches were identified using student initials and birthdates provided on both surveys. 332 matches were identified out of the cleaned dataset. These surveys were used for item and survey validation discussed in Section 4.5.

Background Item 25 on GECI.vC asked each student "Have any of your other classes besides this course covered the greenhouse effect during this semester?" This item was intended to identify and remove any students who may have received additional education treatments besides the specific intervention being studied (see Section 4.3). If a student answered Item 25 affirmatively on the post-instruction survey, both the pre- and post-instruction survey for that student were removed from the dataset. This reduced the number of matched surveys by roughly 15% and resulted in a final total of 273 survey matches.

Finally, it is important to clarify that the timing of the pre-instruction survey, intervention, and post-instruction survey varied between the astronomy, planetary science, and atmospheric science classes, as shown in the Table 4.4 below.

Table 4.4 Timing of surveys and interventions

Class Type	Class Periods (Total Time)	Time between pre-survey & intervention	Time between intervention & post-survey
Astronomy (2)	1 TR (50-60 min)	2 weeks (including SB)	Next class period
Atmospheric Science (2)	4 MWF / 3 TR (150-190 min)	1 week	4 weeks (including SB)
Planetary Science (1)	2 TR (150 min)	6 weeks (including SB)	3 weeks
Planetary Science (1)	5 TR (375 min)	7 weeks (including SB)	Next class period

*SB = Spring Break

The surveys in the two astronomy classes occurred much closer to the intervention than in the other classes, with the post-survey being administered at the start of the very next class day after the intervention. For the atmospheric science course, constraints imposed by the course instructor did not allow for administration of the post-survey immediately following the intervention; rather, 4 weeks elapsed between the interventions and post-testing. In the planetary science classes, the interventions occurred over a month after the pre-survey. In one planetary science class, the post-instruction survey was administered 3 weeks following instruction; in the other, the survey was given the next class period. Thus, while it is possible to compare amongst the two astronomy classes, the two atmospheric science classes, and the two planetary science classes, the above inconsistencies make it unreasonable to compare post-instruction results and learning gains between each of these groups.

It is also important to note that many students in the atmospheric science class spent additional time covering the greenhouse effect outside of class while working on homework and studying for exams on the topic. Students in the planetary science classes had a homework assignment on the topic. No data was collected on how much time each student spent on these additional activities. Students in the astronomy classes did not spend out-of-class time on the topic because they were post-tested the next class day after instruction.

4.5 Validation of GECI.vC

The most traditional validation measure for a survey instrument like the GECI involves analyzing learning gains by comparing pre- and post-instruction scores for students receiving educational treatment. Presumably, if both the survey instrument and the educational intervention are effective, one would expect to see learning gains. Discussion of this analysis is saved for Section 4.7 when learning gains are compared between the various treatment groups described above.

However, described first are several additional validation tools that were applied to data from the GECI.vC survey to test for internal consistency, survey sensitivity, and a balance of item difficulties. These include an analysis of Cronbach's alpha, effect size, and normalized gain for the entire survey instrument and, for each survey question, and analysis of item difficulty, item discrimination, normalized gain, and distracter frequencies. Because each of these can be conducted without regard for the specific type of educational treatment, all 332 cleaned matches used for the validation analyses presented in this section.

4.5.1 Whole Survey Validation

One important measure of a multiple-item concept inventory involves internal consistency. If the instrument is to survey student understanding on a particular topic and measure whether learning has occurred on that topic, student responses to the multiple items should be correlated with one another in some way. Cronbach's alpha is one measure for assessing internal consistency:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum s_i^2}{s_T^2}\right)$$

The metric attempts to quantify whether different survey items characterize the same phenomenon (Bland and Altman, 1997). Here, k is the number of survey items, s_i^2 is the variance of the ith survey item, and s_T^2 is the variance of the total score obtained by summing all the survey items. If a group of variables is independent, the variance of the total score obtained from combining these items (s_T^2)is equal to the sum of the variances ($\sum s_i^2$) and Cronbach's alpha will have a null value. However, if the variables are correlated, the s_T^2 will be larger, resulting in a larger Cronbach's alpha with an upper limit of unity.

Cronbach's alpha was calculated for both the pre-instruction and post-instruction survey GECI.vC using data from only students with a matched survey sets (n=322). A value of 0.60 was obtained pre-instruction and 0.79 post-instruction. One way to interpret this result is that 79% of the variance of the total scores obtained post-instruction is a reliable variance and not due to random chance. According to Bland and

Altman (1997), values of 0.7 to 0.8 are reasonable values for comparing groups in non-clinical situations.

A second approach for assessing the efficacy of the survey instrument involves looking for statistically significant differences between pre- and post-instruction performance. Two measures of this are effect size and normalized gain. Effect size is a measure of the difference between two groups in units of standard deviation. Several techniques exist for calculating effect size. Given that the standard deviations for both the pre- and post-instruction samples were known, Hedge's *g* was calculated:

$$g = \frac{\left|\overline{X}_1 - \overline{X}_2\right|}{\hat{\sigma}_{Pooled}} \qquad \text{where} \qquad \hat{\sigma}_{Pooled} = \sqrt{\frac{(n_1 - 1)\hat{\sigma}_1^2 + (n_2 - 1)\hat{\sigma}_2^2}{(n_1 - 1) + (n_2 - 1)}}$$

Using the mean score ($\overline{X}$), standard deviation ($\hat{\sigma}$), and number of surveys (n) for both pre- and post-instruction samples, the Hedge's *g* value obtained for this study is 1.47. For research in the behavioral science, health science, and education, a *g* value of 0.2 and 0.5 are considered small and medium effects, respectively. An effect size of 0.8 or greater is considered a large effect (Kirk, 1999, page 397). Thus, the GECI.vC survey was able to measure a large effect between student understanding before and after instruction.

Another standard metric, especially in physics education research, for measuring pre- and post-instruction differences is normalized gain. Here, difference before and after instruction are weighted by the potential for improvement based up pre-instruction performance:

$$\langle g \rangle = \frac{\%\langle post \rangle - \%\langle pre \rangle}{\langle 100 - \%\langle pre \rangle \rangle}$$

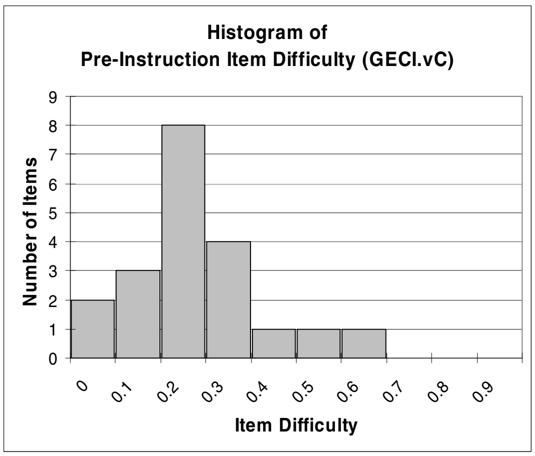
Here $\langle pre \rangle$ and $\langle post \rangle$ represent the mean score of the pre- and post-instructional groups (Hake, 1998). Again, all six classes have been grouped on the basis that all students received some type of treatment on the greenhouse effect. The calculation is also still limited to the 332 students with matched pre- and post-instruction surveys. The value obtained for normalized gain on the entire instrument is 0.37. Values between 0.3 and 0.7 are considered "medium gain." Section 4.7 describes normalized gains by class to provide insight into how different treatment groups performed on the GECI.vC post-instruction.

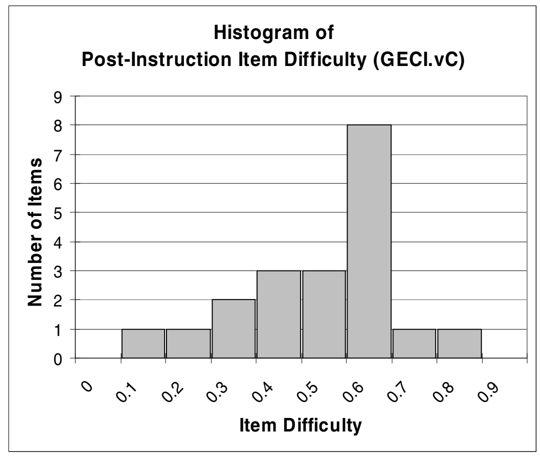
4.5.2 Item Validation

The previous three metrics (Cronbach's alpha, effect size, and normalized gain) have been applied to the combined data from all items of the survey together. Additional validation is provided by looking at survey items individually. As described below, the four metrics applied at the item level included item difficulty, item discrimination, normalized gain, and distracter frequencies.

Item difficulty (p) is simply the proportion of students who answered the survey item correctly. As defined, more difficult survey items have a lower item difficulty value than easier questions (Allen & Yen, 1979). While somewhat counter-intuitive, this standard education research convention is used here even though item difficulty is the inverse of what a layperson would consider "item easiness." Figure 4-1 below provides histograms of the 20 GECI survey items binned by item difficulty both before and after instruction.

Figure 4-1 Item analyses and validation for GECI.vC





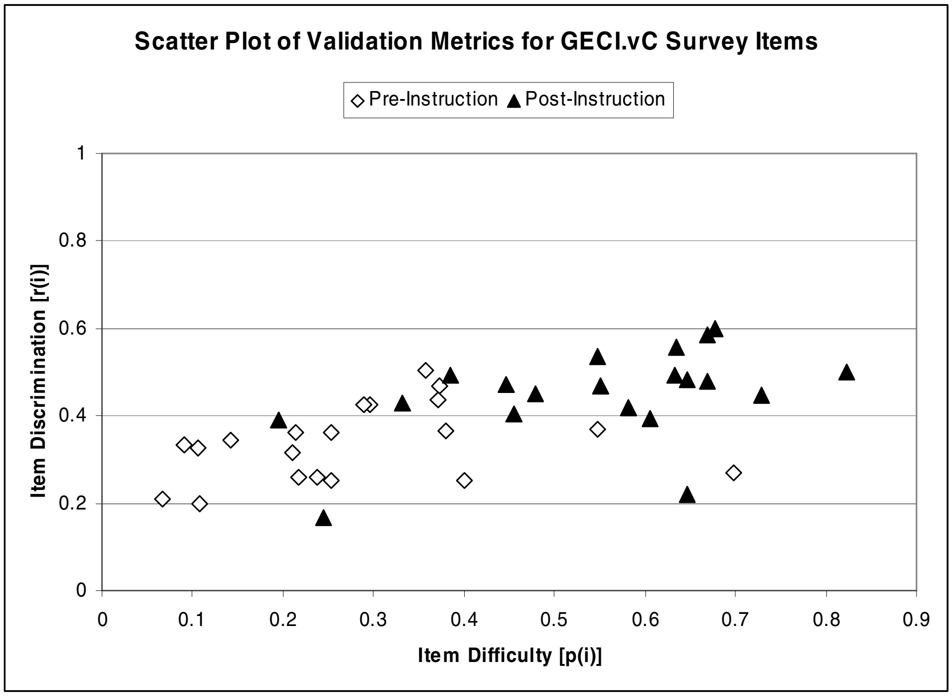
As these graphs show, students performed better on the survey post-instruction with a higher fraction of students answering each item correctly. Also, a range of item difficulties is found both before and after instruction. Ensuring that both more and less challenging items are found on the instrument is an important aspect of an effective concept inventory design.

A second instrument validation metric is item discrimination. Item discrimination relates how well students perform on a specific item compared to the entire instrument (Allen & Yen, 1979). The measure for item discrimination (r_i) used here involves item difficulty for the item and the statistical significance of any deviation between the mean survey score of students answering the item correctly and the mean survey score of all students:

$$r_i = \frac{\overline{X}_i - \overline{X}}{s_X}\sqrt{\frac{p_i}{1-p_i}}$$

Here, p_i is the item difficulty for a given item, $\overline{X}_i$ is the mean survey score calculated for all student who answered the survey item correctly, and $\overline{X}$ and s_x are the mean survey score and standard deviation, respectively, of all students. For an easier survey items with larger *p* value, the increased square-root term of this metric partially offsets the expected decrease in the first term of the formula, the differential between mean survey scores for the two described groups. A low item discrimination value is obtained if very few students get the item correct (low *p*) and there is little correlation between how well these students did on the remainder of the survey compared to those who answered the item incorrectly. An especially difficult survey item with a low p value will still have a high *r* value if students answering the item did significantly better on the survey as a whole than their counterparts an thus produces a high discrimination value. High item discrimination values across a range of item difficulties are generally desirable for an effective survey instrument. Figure 4-2 below compares item difficulty and item discrimination values obtained for each of the 20 GECI.vC survey items both before and after instruction.

Figure 4-2 Scatter plot of difficulty and discrimination for GECI.vC items



Open diamonds represent pre-instruction survey data, closed triangles post-instruction.

The figure shows a range of item difficulties with a shift towards more students answering items correctly post instruction. Item discrimination values are respectably high pre-instruction (mean = 0.34) and generally increase following instruction (mean = 0.45).

Two other metrics were also applied at the item level: normalized gain and distracter frequencies. As discussed in Section 4.5.1, normalized gain provides a measure of post-instruction gains normalized to pre-instruction scores. Normalized gain takes into account the fact that easier items with higher *p*-values have less room measuring student improvement through instruction than more difficult items with low *p*-values. In addition, insight can be gained by looking at commonly selected distracters both before and after instruction. Table 4.5 below provides a summary of all four metrics discussed above for each of the 20 items on GECI.vC. Here, survey items have been grouped into the five thematic categories described previously in Section 4.2.

Table 4.5 Item validation results for GECI.vC survey

Version	Pre-Item Diff. (p)	Post-Item Diff. (p)	Pre-Item Disc. (r)	Post Item Disc. (r)	Norm. Gain	Pre-Correct Resp.	Pre-Best Distract	Post-Correct Resp.	Post-Best Distract
GHG									
1 - H_2O is the most abundant greenhouse gas	0.105	0.446	0.326	0.470	0.38	B 10.5%	A 67.8%	B 44.6%	A 46.4%
8 - O_2 is not a greenhouse gas	0.238	0.244	0.260	0.168	0.01	D 23.8%	C 31.9%	D 24.4%	C 38.3%
16 - H_2O and CO_2 two most abundant greenhouse gases	0.253	0.636	0.361	0.557	0.51	E 25.3%	D 26.2%	E 63.6%	D 15.4%
EM									
10 - Sun mainly radiates VIS & IR	0.090	0.386	0.332	0.492	0.32	D 9.0%	C 38.6%	D 38.6%	C 34.6%
14 - Sun mainly radiates VIS	0.108	0.331	0.199	0.428	0.25	C 10.8%	D 56.3%	C 33.1%	D 35.5%
2 - Atmosphere mainly absorbs IR	0.211	0.633	0.317	0.492	0.53	B 21.1%	D 70.5%	B 63.3%	D 27.1%
17 - Atmosphere mainly radiates IR	0.373	0.669	0.466	0.480	0.47	B 37.3%	C 18.4%	B 66.9%	C 14.2%
12 - Surface mainly absorbs VIS & IR	0.142	0.548	0.344	0.536	0.47	D 14.2%	B 40.4%	D 54.8%	B 24.1%
6 - Surface mainly radiates IR during nighttime	0.548	0.822	0.370	0.501	0.61	B 54.8%	A 14.8%	B 82.2%	A 6.3%
20 - Surface mainly radiates IR during daytime	0.295	0.648	0.425	0.482	0.50	B 29.5%	C 37.0%	B 64.8%	C 22.6%
EQ									
3 - Energy leaving equals energy arriving	0.217	0.605	0.259	0.395	0.50	C 21.7%	B 39.2%	C 60.5%	B 23.8%
15 - Energy flow diagram of solar and terrestrial radiation	0.380	0.581	0.365	0.417	0.33	D 38.0%	C 21.7%	D 58.1%	E 15.7%
18 - Energy exchange btw surface and atmosphere	0.253	0.455	0.252	0.403	0.27	E 25.3%	C 28.3%	E 45.5%	C 20.8%
19 - Surface absorbs VIS and radiates IR	0.401	0.551	0.252	0.470	0.25	B 40.1%	A 32.8%	B 55.1%	A 17.2%
MECH									
4 - Greenhouse gases transparent to some energy	0.066	0.196	0.209	0.389	0.14	E 6.6%	C 47.3%	E 19.6%	C 46.7%
7 - GHE influences flow of energy through atmosphere	0.214	0.479	0.362	0.452	0.34	C 21.4%	B 42.2%	C 47.9%	B 19.6%
11 - Greenhouse gases absorb and give off specific energies	0.370	0.729	0.436	0.446	0.57	B 37.0%	A 35.8%	B 72.9%	D 12.3%
GW									
5 - GHE is old process involving gases and energy	0.289	0.669	0.424	0.586	0.53	D 28.9%	A 34.0%	D 66.9%	A 13.9%
9 - Increase in GHE may be causing GW	0.699	0.648	0.270	0.220	-0.17	B 69.9%	C 15.4%	B 64.8%	C 18.4%
13 - GHE occurs naturally even without human civ	0.358	0.678	0.503	0.600	0.50	A 35.8%	C 28.9%	A 67.8%	B 14.5%
minimum value	0.066	0.196	0.199	0.168	-0.17				
maximum value	0.699	0.822	0.503	0.600	0.61				
mean value	0.281	0.548	0.337	0.449	0.37				

Note on this table that the item difficulty matches the percentage of students choosing the correct response for each item. This table provides a compact quantitative summary of all item validation measures described above. Ideally, one would expect to measure gains on every item. However, as the table shows this is not the case for Items 8 and 9. Each of these items is considered separately below.

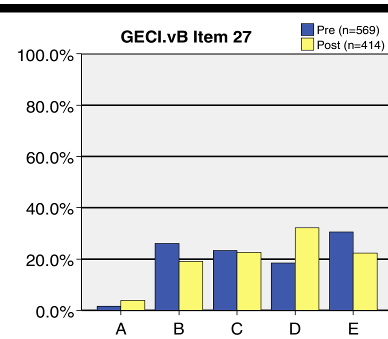
Item 8 was one of three items regarding the identity of greenhouse gases with essentially zero gain following instruction. Returning to the response frequency histogram for this item discussed previously in Section 3.8, the item was asked on two different versions of the GECI.

Table 4.6 Analysis of GECI.vC Item 8

<u>GECI.vB: Item 27</u>

Which one of the following is <u>not</u> a greenhouse gas?

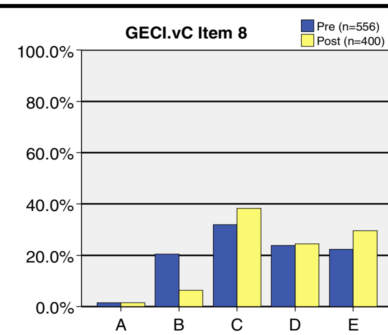
a) carbon dioxide (CO2)
b) water vapor (H2O)
c) methane (CH4)
d) oxygen (O2)
e) ozone (O3)



<u>GECI.vC: Item 8</u>

Which one of the following is <u>not</u> a greenhouse gas?

a) carbon dioxide (CO_2)
b) water vapor (H_2O)
c) methane (CH_4)
d) oxygen (O_2)
e) ozone (O_3)



These histograms indicate that student strongly identified throughout that carbon dioxide is a greenhouse gas. The student surveyed during Fall 2005 on GECI.vB also showed positive learning gains that oxygen is not a greenhouse gas. Students from the Spring

2006 administration of GECI.vC learned through instruction that water vapor is also a greenhouse gas, but did not show gains that oxygen is not a greenhouse gas. Instead, the other distracters of methane and ozone were equally attractive with methane actually being selected most frequently. The item also had the lowest item discrimination value post-instruction, indicating that student responses to this item were not correlated well with student understanding of other items on the survey. It is apparent that the six classes surveyed during Spring 2006 (primarily planetary science and astronomy courses) did not cover the identity of greenhouse gases as thoroughly as classes from the previous semester, including a larger percentage of atmospheric science and global change courses. While analysis of the GECI.vC results could be used to justify removal of the survey item from the instrument, it was decided to retain this survey item based upon the measurable gains found with a larger and more diverse survey group during Fall 2005.

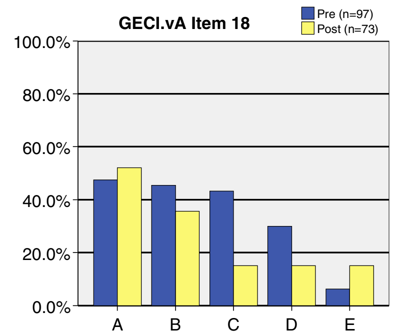
Item 9, one of three items regarding student distinctions between the greenhouse effect and global warming, actually resulted in a negative normalized gain. The survey item was a revised item from GECI.vA asking students to describe that an increase in the greenhouse effect is causing of global warming. This previous item had a good distribution of pre-instruction responses but showed weak learning gains post-instruction. However, as the response frequencies below show, the revision appears to have made the item even weaker by making the answer too obvious.

Table 4.7 Analysis of GECI.vC Item 9

<u>GECI.vA: Item 18</u>

Which of the following describes the cause(s) of global warming? Circle all that apply.

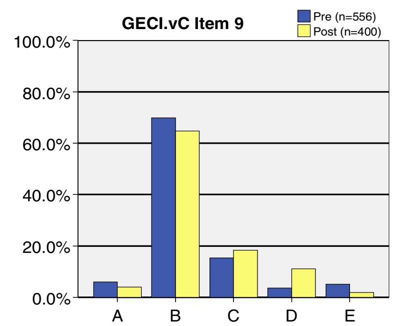
- **a) Increase of the greenhouse effect causes global warming.**
- b) Decrease of ozone causes global warming.
- c) Increase of the greenhouse effect causes decrease of ozone which causes global warming.
- d) Decrease of ozone causes increase of the greenhouse effect which causes global warming.
- e) None of the above.



<u>GECI.vC: Item 9</u>

Which of the following best describes the relationship between the greenhouse effect and global warming?

- a) The greenhouse effect and global warming are the same thing.
- **b) An increase in the greenhouse effect may be causing global warming.**
- c) Global warming may be causing an increase in the greenhouse effect.
- d) The greenhouse effect and global warming are likely unrelated.
- e) There is no definite proof that either the greenhouse effect or global warming exist.



Item 9 had the highest pre-instruction *p*-value found on the GECI.vC, with almost 70% of the students answering the item correctly, and a very low common distracter frequency of 15%. Both of these characteristics conspired against the item showing significant learning gains. The item is also one of the more wordy items on the survey and is largely concerned with semantics of global warming and the greenhouse effect rather than cognitive reasoning abilities about either phenomenon. Finally, the item had the second lowest item discrimination value post-instruction, again indicative of the fact that performance on this item was not well correlated with performance on the survey as a whole. Other related items on previous surveys also did not show significant gains. For these reasons, one could argue that this item should be dropped from the final version of the GECI. This is discussed further in Section 4.8 below.

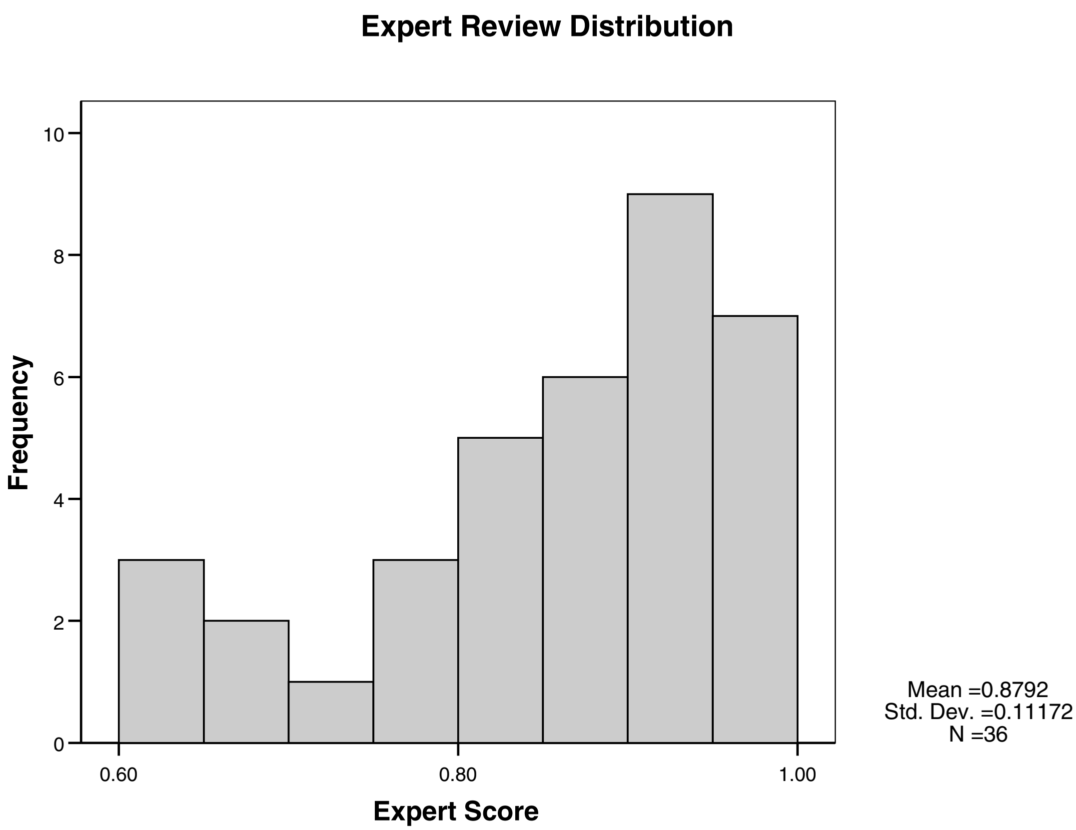
4.6 Expert Review

As an additional validation of the GECI.vC survey, the instrument was administered to individuals with expertise in the field of planetary science and presumably greater familiarity with the greenhouse effect. Survey scores from these "expert reviewers" in the field provide a calibration point for comparison with the undergraduate non-science population for which the survey was targeted. In addition, the expert reviewers were encouraged to attach written comments that provided valuable qualitative feedback on individual survey items.

The expert review involved 36 members of the planetary science department at the University of Arizona. Of these, 21 were graduate students in planetary science, 5 were post-doctoral researchers, and 10 were planetary science faculty and research scientists. The participants were asked to complete a hard copy of the survey without using any references or aids and to return the survey to the researches mailbox.

The following mean scores and standard deviations were found for each of the three groupings: graduate students - 86% (SD=13%), post-doctoral researchers – 86% (SD=7%), faculty – 93% (SD=8%). A one-way ANOVA analysis of the three categories above reveals that the differences shown are not statistically significant at the $p<0.20$ level, $F(2,33)=1.472$. The mean survey score for all participants combined was 88% with a standard deviation of 11%. Use of a t-test shows that this score is significantly higher than the student mean score either pre-instruction (mean=28%, SD=14%, $p<0.001$, t(366)=24.8) or post-instruction (mean=55%, SD=21%, $p<0.001$, $t(366)=9.3$). Graduate students and professionals in the field of planetary science perform significantly higher than undergraduate non-science majors. While at face value, the mean expert score indicates that participants missed between 2-3 survey items, the distribution is both bimodal and negatively skewed as shown in Figure 4-3.

Figure 4-3 Histogram of mean scores from expert review



A quarter of expert participants missed only one item and an additional 19% obtained perfect scores.

The expert review was also helpful in analyzing individual items found on the GECI.vC. First, it should be noted that 12 out of the 20 survey items were answered correctly by over 90% of the expert participants. Table 4.8 below shows the response frequency distribution for the remaining items on which experts agreed less strongly with the instrument designers. Response options selected by two or more participants are listed in descending order of selection frequency.

Table 4.8 Most frequently missed items from expert review

Version	Item Difficulty (p)	Correct Response	Distracter Responses Selected by more than 2 or more participants		
2 - EM atmosphere absorbs IR	0.889	B 88.9%	C 5.6%	D 5.6%	
12 - EM surface absorbs VIS+IR	0.833	D 83.3%	C 11.1%	B 5.6%	
20 - EM surface radiates IR during day	0.778	B 77.8%	C 22.2%		
10 - EM Sun mostly gives of VIS+IR	0.694	D 69.4%	C 27.8%		
14 - EM Sun gives off mostly VIS	0.806	C 80.6%	D 8.3%	B 5.6%	
3 - EQ energy out = energy in	0.778	C 77.8%	B 11.1%	D 5.6%	
15 - EQ diagram	0.889	D 88.9%	A 8.3%		
18 - EQ increase is at surface not space	0.500	E 50.0%	B 33.3%	D 11.1%	C 5.6%

As the table shows, the survey items experts had the most difficulty with were from two thematic categories: 1) types of energy related to the greenhouse effect and 2) energy balance. On Items 10 and 14, a large proportion of expert participants incorrectly indicated that the Sun radiates large amounts of ultraviolet energy. Almost a third of the participants selected “visible and ultraviolet” for Item 10 regarding the two main energies radiated by the Sun and 8% described that the peak energy of the Sun was ultraviolet on Item 14. As one participant explained “Peak of the Planck Curve is in the visible, but more energy in UV than in IR.” While an understanding that the Sun emits much more energy at infrared wavelengths than ultraviolet wavelengths is fundamental to addressing student associations between ozone depletion and the greenhouse effect, a substantial number of experts don't appreciate this characteristic of the Sun. Similar to results from the student population, this misconception carried through to Item 12 (11% selected that the surface mainly absorbs "visible and ultraviolet") and Item 2 where the visible and ultraviolet were common distracters for heating the atmosphere.

Item 20 is the final EM question that experts did not agree on. Over 20% of the participants selected that the surface of Earth gives off or radiates mostly visible energy. It is suspected that several experts who selected visible either did not notice that the questions focused on radiated rather than reflected energy or did not appreciate that the Earth's surface radiates over 16 times more energy as infrared light than it reflects as visible light. One could argue that the item could be made more explicit by underlining the term "radiates," however it is unclear that this term means much to the targeted undergraduate population.

For Items 3 and 15 regarding energy balance, the average score for all expert participants was less than 90%. However, almost all of the students who missed these two items were graduate student. Only one out of the15 non-graduate students answered either of these items incorrectly. The lower scores for these items are attributed to weaker understanding of energy balance amongst graduate students.

While each of the items discussed above reveal nuances in expert understanding of the greenhouse effect, it is not believe that any of the lower scores necessitates revision of these survey items. Only Item 18 warrants attention regarding possible revisions. This item reads as follows:

18) Due to the greenhouse effect, Earth's overall surface temperature is affected primarily by
    a) an increase in energy entering from space.
    b) a decrease in energy leaving to space.
    c) both an increase in energy entering from and a decrease in energy leaving to space.
    d) energy being permanently trapped in the atmosphere.
    e) an increase in the amount of energy absorbed and given off between the surface and atmosphere.

Only half of the expert participants correctly selected Option E, with a third preferring Option B and 11% selecting Option D. Additionally, professionals (faculty and post-doctoral researchers) did not perform significantly better than graduate students. Two experts provided written comments that the question was especially confusing. Interestingly, undergraduate students performed almost as well on this item post-instruction as the experts surveyed here. It appears that while each of the four distracters is definitively incorrect, the wording of the correct option was ambiguous and convoluted. It is possible that participants did not notice that the correct option involves energy being both absorbed and given off at the surface/atmosphere interface. A possible revision would be to rephrase this option to state "an increase in the amount of energy exchanged between the atmosphere and the surface." While further testing and discussion of this item is warranted, the question still has potential to address fundamental misconceptions related to energy balance. If anything, the item has too much potential to address this topic given that even experts had difficulty identifying the correct response.

A final outcome of the expert review process was that participants provided written comments and feedback on individual survey items. Some of these comments revealed reasoning difficulties and misconceptions among the expert participants and did not warrant any survey revisions. Some of the comments asked for levels of detail beyond the level of undergraduate student understanding revealed throughout the survey development process. For example, the following comment with regards to Item 7 was beyond the scope of the survey instrument: "Up to ~60 latitude, direct sunlight is mostly responsible for surface temperature. Greater than 60 degrees, mostly winds transfer energy by circulation." Other terminology-rich suggestions like "Need to specify delta lambda" were also disregarded.

Two comments were determined to merit consideration here. With Items 1 and 16 regarding the identity of greenhouse gases, one participant questioned whether it was more important to survey student understanding of the most "abundant" greenhouse gases or the most "effective" or "important" greenhouse gases. Second, comments for Items 5 and 13 regarding the difference between the greenhouse effect and global warming indicated varying expert opinions regarding the meaning and use of these two terms. Several commented that for Item 5 they wanted to select both Option A (anthropogenic greenhouse effect) and Option D (natural greenhouse effect) as correct responses. For Item 13, one expert suggested "Should you somehow distinguish anthropogenic and natural greenhouse effects throughout?" While not addressed in this work, future efforts to more clearly define student conceptions of the natural atmospheric greenhouse effect caused primarily by water vapor and the anthropogenic greenhouse effect enhanced by carbon dioxide could be developed that would address these expert concerns. The trick is to differentiate between the two processes without providing clues that would bias expression of student beliefs and ideas.

4.7 Instructional Intervention Results

The validation measures discussed above strengthen our confidence in the ability of the GECI.vC to measure learning gains in student understanding regarding the greenhouse effect. A final test of the instrument involves analysis of pre- and post-instruction results amongst the various interventions described in Section 4.3. Table 4.9 re-summarizes the labeling and description of the interventions these various groups received during testing of the GECI.vC.

Table 4.9 Labels and descriptions of intervention groups

Code	Description
ASTR-Absent	Astronomy students receiving no treatment; students were absent from class during greenhouse effect interventions
ASTR-Lecture+LTN	Astronomy students who received lecture and then experienced LT through a one-way narrative provided by the instructor
ASTR-Lecture+LTA	Astronomy students who received lecture and then did LT as small-group in-class activity
ATMO-Lecture	Atmospheric science students who received 150 minutes of lecture and demo about the greenhouse effect
ATMO-Lecture+LTH	Atmospheric science students who received 150 minutes of lecture and demo and also took the LT home with them as a handout
ATMO-Lecture+LTA	Atmospheric science students receiving 150 minutes of lecture and demo and did LT as small-group in-class activity
PTYS-Lecture1	Planetary science students who received ~100 minutes of lecture and did homework assignment on greenhouse effect
PTYS-Lecture2	Planetary science students who received ~100 minutes of lecture and did homework assignment on greenhouse effect

Due to inconsistencies in survey timing discussed in Section 4.3, comparisons are made within the three above groups (ASTR, ATMO, PTYS) but not between groups. Table 4.10 below shows the pre- and post-instruction values used for these comparisons. The table also provides the calculated gain, gain sigma, and effect size for each intervention group (see Section 4.5 for details on these metrics).

Table 4.10 Pre- and post-instruction means and gains by intervention

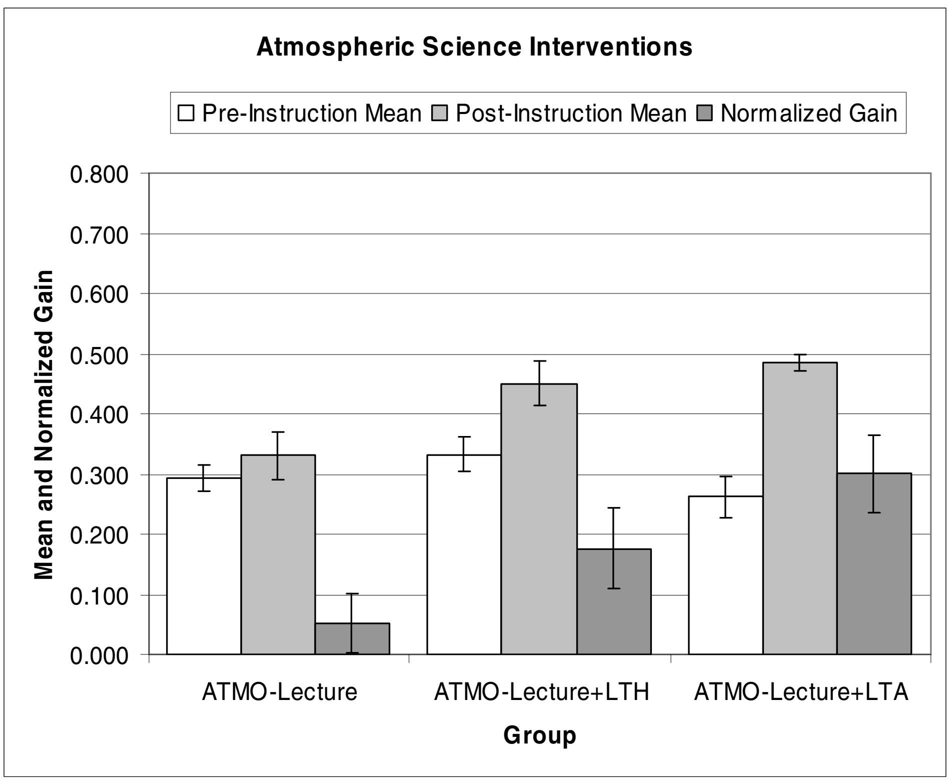
Description	n	Pre Mean	Pre SD	Post Mean	Post SD	Norm Gain	Gain SE	Effect Size
ASTR-Absent	30.00	0.267	0.140	0.373	0.168	0.145	0.051	0.691
ASTR-Lecture+LTN	62.00	0.252	0.122	0.640	0.184	0.518	0.033	2.476
ASTR-Lecture+LTA	69.00	0.262	0.153	0.688	0.155	0.577	0.027	2.768
ATMO-Lecture	33.00	0.294	0.124	0.330	0.160	0.052	0.049	0.254
ATMO-Lecture+LTH	23.00	0.333	0.136	0.450	0.182	0.176	0.067	0.732
ATMO-Lecture+LTA	16.00	0.263	0.138	0.484	0.162	0.301	0.064	1.473
PTYS-Lecture1	19.00	0.274	0.165	0.442	0.174	0.232	0.068	0.992
PTYS-Lecture2	21.00	0.331	0.153	0.590	0.168	0.388	0.063	1.617
Total	273.00	0.276	0.141	0.542	0.214	0.368	0.019	1.470

A one-way ANOVA analysis of the pre-instruction means for all groups reveals that variations in these values around the total mean are not statistically significant, $F(7,265) = 1.469$, $p < 0.178$. Based upon this as well as the nature of NATS enrollment, one can argue that the various interventions involved randomly sample the same student population.

Through the use of a Student t-test, statistically significant differences between pre- and post-instructional means within each intervention group listed above were determined. All differences were found to be significant at the $p<0.01$ level except for Intervention "ATMO-Lecture," which did not pass the t-test at $p<0.10$. Apart from this atmospheric science group, all other intervention groups showed learning gains. Interestingly, even astronomy students who were absent on the day of the greenhouse effect intervention showed a learning gain. This unexpected result may be due to three possible factors: 1) the astronomy class had a quiz immediately following the pre-instruction survey that included some topics on light, and 2) the short time-span between the two surveys may increase scores on the second survey due to familiarization with the survey instrument, 3) students who were absent during the intervention may have copied answers off of other students scantrons.

Finally, normalized gains within each of the three intervention groups are compared separately using Student t-tests. Focusing first on the atmospheric science investigation, Figure 4-4 below shows a comparison of pre- and post-instruction means and normalized gains between the three ASTR intervention groups.

Figure 4-4 Means and normalized gains for atmospheric science sections

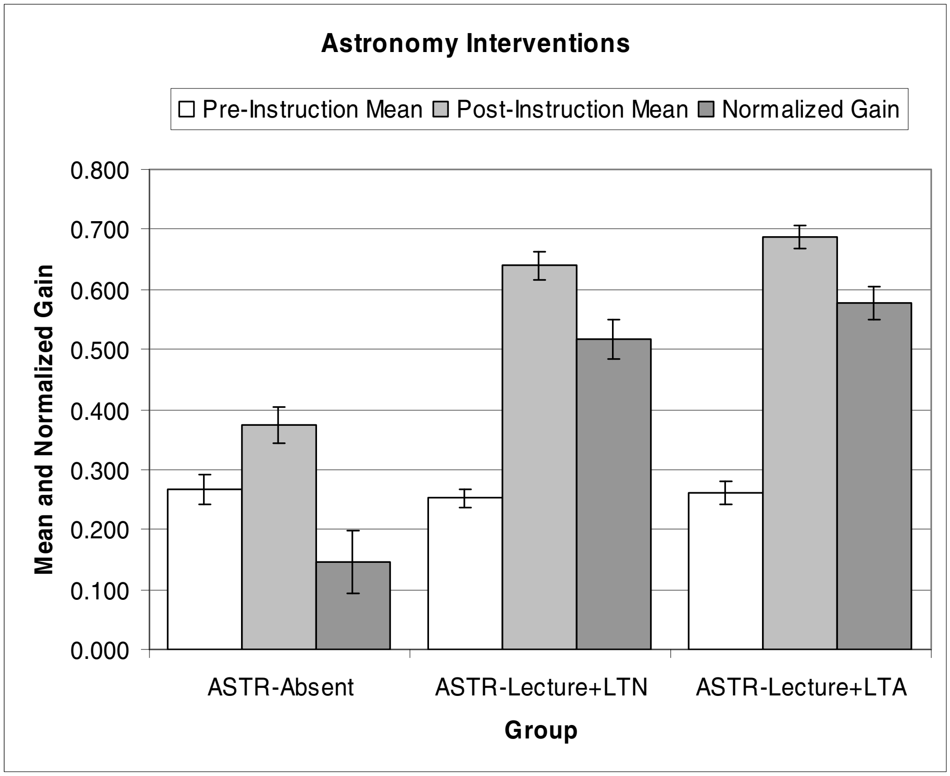


The gain reported for the first group, which received only lecture and an exam on the greenhouse effect, is very mild (0.052 +/- 0.049). Again, the difference in pre- and post-instruction scores was not found to be statistically significant at $p<0.10$. Students in the other section of the course received the Lecture Tutorial either as an activity that they completed in class or as a handout that they may or may not have completed on their own while studying for the exam on the greenhouse effect. Both of these groups show more substantial gains. Using Student t-tests, it was determined that the difference in gain between the ATMO-Lecture and ATMO-Lecture+LTA groups was statistically significant at a level of $p<0.01$. The difference in gain between the ATMO-Lecture and ATMO-Lecture+LTH was significant at the $p<0.05$ level.

The strong gain shown for ATMO-Lecture+LTH is intriguing. These students were in the same section as the ATMO-Lecture+LTA students. To clarify again, these difference between these two groups is that ATMO-Lecture+LTH students did not volunteer to remain in the class to complete the activity but took the activity home with them. The only students who definitively did not receive the LT were those in the ATMO-Lecture group. Based upon observations of both sections, the instructor taught nearly identical lectures, including the same demonstrations and jokes. Both sections took the same exam in between the intervention and the post-instruction survey. Interestingly, on this instructor quiz, the class that did not receive the LT had a mean score of 65% compared to a mean of 73% for the class that received the LT. While not confirmable, one hypothesis as to the success of both the Lecture+LTH group is that some percentage of these students completed the LT outside of class.

Turning to the astronomy intervention study, the following means and gains were found.

Figure 4-5 Means and normalized gains for astronomy sections

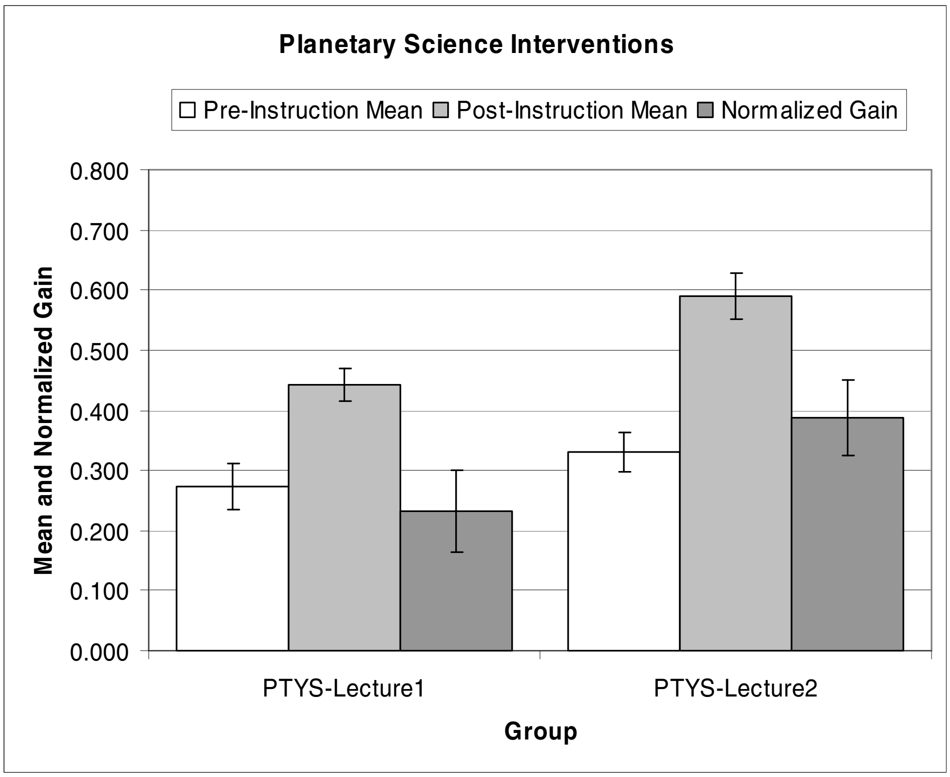


While students who were absent during the treatment day (ASTR-Absent) did show instructional gains, these were significantly lower ($p<.001$) than either of the other two treatment groups (ASTR+LTN and ASTR+LTA). The slightly higher gain for ASTR-Lecture+LTA (0.58 +/- 0.03) than for ASTR-Lecture+LTN (0.52 +/- 0.03) was found to be significant at the $p<.10$ level.

It is important to note that neither of the interventions in the astronomy classes can be classified as traditional lecture. The use of Lecture Tutorials was an important component of the astronomy classes throughout the semester and students recognized that attention to material on Lecture Tutorials was beneficial to success in the class. Students in both classes received instruction on the greenhouse effect using a LT, an activity based upon constructivist theory which confronts student misconceptions and provides a more accurate scientific alternative. Finally, the instructor leading these interventions was highly involved in the development of both the GECI survey and the LT and was particularly aware of the central misconceptions these instruments address. This allowed the instructor to provide a highly informed narrative on the LT in which he was able to explain student reasoning to both correct and incorrect responses to questions on the tutorial meant to specifically address student misconceptions. While it is obvious that students in the ASTR-Lecture+LTA group received an interactive treatment on the greenhouse effect, it is argued that students in the ASTR-LTN group also received a highly non-traditional lecture. The Lecture Tutorial Narrative that they received was a focused presentation of the Lecture Tutorial and students paying attention to the narrative likely experienced cognitive conflict and resolution similar to students who completed the activity in small groups. While these students were never asked to give or share their answers and thoughts with other students, they were asked all the same questions in a one-way discussion led by the instructor. Thus, neither of the astronomy groups discussed above is considered to be traditional lecture interventions.

Means and gains for the PTYS class are presented in Figure 4-6 below. No attempts were made to standardize the treatments between these two groups. The two sections were taught by different instructors and had different homework assignments on the greenhouse effect. The PTYS-Lecture 1 course covered the topic for 150 minutes of class time and was surveyed 2.5 weeks after instruction. The PTYS-Lecture 2 course covered both the greenhouse effect and global warming for 375 minutes and was surveyed the day after the final discussion of these topics.

Figure 4-6 Means and normalized gains for planetary science sections



Both classes show significant learning gains, with the difference between the pre- and post-instruction means being significant at a level of $p<0.01$. Also, the difference in gain between the two PTYS classes is statistically significant at the $p<.05$ level.

The astronomy treatment groups showed the highest gains of all intervention groups, but the reader is again cautioned that the post-instruction survey was administered closer to the intervention than with other groups. The post-instruction survey was administered immediately following intervention in the astronomy classes while several weeks transpired with the other classes. It is unclear whether the astronomy treatments would have revealed different retention rates if the survey had been given later in the semester. One argument for stronger student performance immediately following instruction is that survey content is fresher and easier to recall from short-term memory. The counterargument is that students who have more time to study the content in preparation for subsequent exams might have a more strongly reinforced understanding later on the semester. In particular, the atmospheric science course had an exam focused partially on the greenhouse effect between instruction and the post-instruction survey.

With regards to the two research questions posed in Section 4.3 for the ASTR group, both interventions involving the LT (ASTR-Lecture+LTA and ASTR-Lecture+LTN) had measurable impacts on student understanding of the greenhouse effect as measured by the GECI.vC. Second, the difference in gain between the LTA and LTN groups is significant at the level of $p<0.10$. Thus, strongly significant differences in learning gains were not found between the group of students who completed the LT in small groups versus students who received a unique and non-traditional lecture narrative on the LT questions. However, it is again noted that both interventions involved focused attention on the LT. An interesting future study regarding the question of equal class time would be to involve instructors who were not involved in the development of the LT activity. These instructors could compare results between giving a traditional 50 minute lecture on the greenhouse effect versus a condensed 25 minute lecture along with the 25 minute LT activity.

Further insight can also be gained by comparing the LT treatment groups with the results from the traditional-lecture style planetary science classes described below. The most appropriate comparison group is PTYS-Lecture2. This group received 375 minutes of traditional lecture and also completed a homework assignment on the greenhouse effect. The astronomy courses covered the topic for a much shorter amount of class time (50-60 minutes). All three groups were surveyed immediately following instruction, thus removing timing concerns raised in the previous paragraph. The ASTR-Lecture+LTA gain of 0.58 +/- 0.03 is significantly higher than the PTYS-Lecture 2 gain of 0.39 +/- 0.06, passing a Students t-test at the $p<0.01$ level. The ASTR-Lecture+LTN gain (0.52 +/- 0.03) is higher than the PTYS-Lecture2 gain at the $p<0.03$ level. Thus, the inclusion of the LT activity produced significantly higher gains in both cases than spending over 6 times more time using traditional lecture and homework.

Taken together, these intervention analyses also indicate that the GECI.vC is effective at identifying learning gains for various learning interventions. While this preliminary intervention attempt introduces several questions as to why various treatments resulted in different gains, it is clear that instruction affects performance on the survey. The following recommendations have been identified to improve future studies: 1) If possible, standardize the timing of pre-instruction and post-instruction survey administration amongst all classes. 2) Do not pass out LT activity until after students have volunteered to participate in the in-class activity. 3) Involve more instructors who were not involved in the development of the survey instrument and LT activity.

4.8 Final Greenhouse Effect Concept Inventory (GECI)

While the previous analysis validates the effectiveness of Survey GECI.vC which was tested during Spring 2006, potential improvements to the instrument were identified through this process. The following revisions have been made to the final version of the Greenhouse Effect Concept Inventory (GECI) provided in Appendix O. The wording of Item 18 has been slightly revised based upon the low score for this item during the expert review. Rather than referring to "an increase in the amount of energy absorbed and given off between the surface and the atmosphere," Option E now states: "an increase in the amount of energy exchanged between the surface and atmosphere." Two other minor wording suggestions resulted from expert review, neither of which significantly alters the nature of the survey. First, a typographic error noted for Item 12 has been corrected by adding the term "by" to the middle of the stem. Second, the phrase "among Earth's surface, the atmosphere, and outer space" has been added to the end of the stem for Item 15. While these modifications are minor, future use of the final GECI will provide data to confirm the effectiveness of these revised survey items and the survey instrument as a whole.

As discussed in Section 4.6, two survey items deserve special attention. Testing of Items 8 and 9 resulted in zero and negative learning gains, respectively. Because Item 8 shows a low pre-instruction item difficulty (0.238), the low gain for this item is likely related to insufficient instruction rather than an inherent flaw with the item. While the item should be scrutinized through future administrations of the GECI, it is recommended that it be retained. On the other hand, Item 9 regarding global warming and the greenhouse effect has an extremely high pre-instruction item difficulty (0.699). This significantly weakens the item's ability to distinguish learning gains. It is likely that this survey item will be removed or replaced on the final version of the GECI that is planned for publication. Pending this publication, though, both Items 8 and 9 are retained for now on the final GECI survey instrument provided in Appendix O.

4.9 Conclusions and Future Work

Several key outcomes have resulted from the research effort described in the previous four chapters. First of these is the creation the GECI survey, a validated concept inventory instrument focused on student understanding of the greenhouse effect for use in the science education research community. Second, the study has confirmed that several previously identified beliefs and reasoning difficulties are also present within the studied population of US undergraduate non-science majors. These include the correct belief that carbon dioxide is an important greenhouse gas and that the greenhouse effect causes an increase in surface temperatures. The students sampled also frequently associate the greenhouse effect with increased penetration of sunlight due to ozone depletion, trapping of energy within the atmosphere, and air pollution. Third, the study branched from previous research on the enhanced greenhouse effect to focus more specifically on physical aspects of the natural greenhouse effect. Key results include identification of student beliefs that the Sun primarily radiates ultraviolet energy, that greenhouse effect can involve trapping of matter (gases, molecules, pollutants) as well as energy, that radiation of energy from the planet surface occurs during the nighttime rather than the daytime, and that energy is permanently rather than temporarily trapped. Finally, a

Lecture Tutorial activity was developed and tested in an attempt to address several of these student reasoning difficulties.

Several opportunities exist to expand upon this research effort into the future. First and foremost, use of the GECI research instrument should be expanded beyond the University of Arizona campus where it was developed and tested. This effort will be facilitated through planned publication of a manuscript describing the development and validation of the instrument and promoting the use of the GECI nationwide. This effort will confirm whether student beliefs identified in this research study are unique to just one population or, more likely, held widely by undergraduate students nationwide. Secondly, the survey instrument can be tested with science majors as well as non-science majors. Preliminary results from testing with three chemistry classes indicate that science majors and non-science majors hold similar misconceptions on this topic. Both of these research efforts will provide additional data useful for further validation of the final GECI instrument.

The GECI survey can also be used to test the effectiveness of various instructional approaches on this topic. As described in this chapter, preliminary attempts were made to do this during the Spring 2006 semester. The following improvements are recommended in these future efforts. First, the research instrument should be administered to a control group of students who do not receive instruction on the greenhouse effect. Control groups sampled pre- and post-instruction using Survey GECI.vA and GECI.vB did not show instructional gains. A similar test should be conducted with the final GECI instrument. Second, the preliminary studies involving testing of a Lecture Tutorial activity on the greenhouse effect should be repeated with some modifications. The study with the atmospheric science class involving use of the Lecture Tutorial activity in addition to lecture could be improved by not passing out the LT activity until after students have consented to complete the activity in class. Results from the students who never received the LT activity would then be more meaningful than those provided here. The study involving equal time on topic with the astronomy class should also be repeated utilizing instructors who are not as deeply involved in the development process of the instrument and activity. Additional educational approaches regarding the greenhouse effect should also be tested using the GECI instrument. These include the use of traditional lectures, classroom demonstrations, classroom debates, individual and group projects, laboratory activities, and ranking task exercises on the topic of the greenhouse effect. Whether the post-instruction survey is administered immediately following the intervention or at the end of the semester (or both) will depend upon the research goals of the project.

Finally, the topics of the greenhouse effect and global warming will continue to be prominent in scientific, political, and public arenas throughout future decades. It will be interesting to compare response frequencies and pre-instruction performance on the GECI over the next several decades. There is definitely room to expand upon the work presented here to elicit and address student beliefs and reasoning difficulties regarding the anthropogenic greenhouse effect and global climate change compared to the natural greenhouse effect. Student understanding of the natural greenhouse effect and flow of energy through the atmosphere is a foundation for understanding the anthropogenic greenhouse effect and climate change. However, research regarding student beliefs and reasoning difficulties with regards to various radiative forcing mechanisms and climate feedback loops promises to be rich, informative, and imperative as we strive to better understand and address global warming and the potential for substantial climate change throughout the remainder of this century.

CHAPTER 5: EQUATORIAL AND MID-LATITUDE DISTRIBUTION OF CHLORINE MEASURED BY MARS ODYSSEY GRS

From a paper accepted for publication with the same title, by:

> J.M. Keller, W.V. Boynton, S. Karunatillake, V.R. Baker, J.M. Dohm, L.G. Evans, M.J. Finch, B.C. Hahn, D.K. Hamara, D.M. Janes, K.E. Kerry, H.E. Newsom, R.C. Reedy, A.L. Sprague, S.W. Squyres, R.D. Starr, G.J. Taylor, and R.M.S. Williams (2007), *Journal of Geophysical Research,* doi:10.1029/2006JE002679, in press.

5.1 Preface

This chapter presents a second research project involving the global distribution of chlorine at the near-surface of Mars measured by the Mars Gamma Ray Spectrometer (GRS). As mentioned briefly in Section 1.1, I was interested in pursuing a graduate student experience that would enrich my understanding of and skills in both science education research and planetary science research. The combination of education research into student misconceptions of the greenhouse effect and planetary science research into analysis and interpretation of gamma ray spectrometer data from Mars has helped fulfill this goal. I originally joined the Mars GRS science team as a Spacegrant Graduate Fellow to work on an education and public outreach project in which Mars data was to be presented musically. This product, termed an auditory display, was developed and tested during the first year of the fellowship. In working with science members on this project, I learned more about and became interested in gamma ray spectrometry applied to planetary science. The project described below evolved through collaboration with Bill Boynton and other members of the GRS science team. My involvement with these individuals on both this project and related education and public outreach projects has been extremely meaningful and instructive during my time at the Lunar and Planetary Laboratory. The remainder of this chapter presents work accepted for publication in the Journal of Geophysical Research (Keller, 2007). This has been reproduced below by permission of the American Geophysical Union.

5.2 Abstract

The 2001 Mars Odyssey Gamma Ray Spectrometer (GRS) has made the first measurement of the equatorial and mid-latitude distribution of Cl at the near-surface of Mars. A mean concentration value of 0.49 wt% Cl has been determined from a grand sum of GRS spectra collected over the planet excluding high latitude regions. Cl is significantly enriched within the upper few tens of centimeters of the surface relative to the martian meteorites and estimates for the bulk composition of the planet. However, Cl is not homogeneously distributed and varies by a factor of ~4 even after smoothing of data with a 10º-arc-radius filter. Several contiguous, geographically large (>20º) regions of high and low Cl concentrations are present. In particular, a region centered over the Medusae Fossae Formation west of Tharsis shows significantly elevated Cl. A large region north of Syrtis Major extending into Utopia Planitia in the northern hemisphere shows the lowest Cl concentrations. Based upon hierarchical multivariate correlations, Cl is positively associated with H while negatively associated with Si and thermal inertia. We discuss four possible geologic mechanisms (aeolian, volcanic, aqueous, and hydrothermal) that may have affected the Cl distribution seen by GRS. While some of the distribution may be due to Cl-rich dust deposits transported by aeolian processes, this

mechanism does not appear to account for all of the observed variability. We propose that reactions with volcanic exhalations may have been important for enriching Cl in Medusae Fossae Formation material.

5.3 Introduction

Chlorine has been recognized as an important chemical component of the martian surface since its detection in fine materials measured at both Viking lander sites in 1976 (1976; Clark and van Hart, 1981; Clark et al., 1982). Based upon oxygen isotope data for the Shergottite-Nakhlite-Chassignite (SNC) meteorites, current estimates place the elemental abundance for Cl in the martian mantle and crust around 150-320 ppm (Lodders and Fegley, 1997; Rao et al., 2005). Concentrations of Cl at the surface are much higher than this bulk abundance, with published values for the soils measured at landing sites ranging between 0.3 and 1.2 wt% (Clark et al., 1982; Wänke et al., 2001; Brückner et al., 2003; Foley et al., 2003; Gellert et al., 2004; Rieder et al., 2004; Gellert et al., 2006). Rao et al. (2002) estimated that a Cl abundance of ~0.3 wt% within the upper hundred meters of the martian regolith is consistent with isotopic excesses measured in martian meteorites of ^{36}Ar and ^{81}Kr, isotopes produced at the near-surface through neutron capture interactions involving Cl and Br. Rather than processes of chemical fractionation or planetary differentiation, secondary surface processes likely account for the enhanced surface Cl abundance over bulk planet estimates (e.g., Clark and van Hart, 1981; Lodders and Fegley, 1997). Mechanisms proposed to account for the enrichment of Cl at the surface include: volatile release associated with volcanic activity, chemical weathering of igneous rocks, and concentration through the processes of water transport, hydrothermal alteration, evaporation, and wind (e.g., Settle, 1979; Clark and van Hart, 1981; e.g., Banin et al., 1997; Bell et al., 2000; Rao et al., 2005). An outstanding question remains as to the degree, duration, and spatial extent over which these mechanisms have altered the Cl concentration. The GRS measurement of the distribution of Cl at the equator and mid-latitudes provides a robust dataset useful for understanding these processes and for providing insight into the evolution and history of the martian surface.

The importance of globally distributed dust and its effects on remote sensing attempts to characterize the surface of Mars have been noted throughout the literature (Christensen, 1986; Christensen and Moore, 1992; e.g., Bandfield et al., 2000). Striking similarities in the elemental composition of soils at each of the landing sites have led to hypotheses regarding a homogeneous global fine component mixed through impact events and dust storms (e.g., Clark et al., 1982; Wänke et al., 2001; Gellert et al., 2004; Yen et al., 2005). Soils and dust are generally higher in Cl and S than local rocks, and variations in concentrations of both elements have been measured at the landing sites (Clark et al., 1982; Wänke et al., 2001; Brückner et al., 2003; Foley et al., 2003; Gellert et al., 2004; Rieder et al., 2004). Attempts have been made to distinguish between rock and salt components of these soils (e.g., Wänke and Dreibus, 1994; e.g., Bell et al., 2000). Outstanding questions exist concerning the distribution, depth, and composition of globally distributed fine materials across Mars.

We report here the first measurements of the equatorial and mid-latitude distribution of Cl at the near-surface of Mars. Previous remote sensing attempts to measure Cl-bearing materials on a global scale using infrared spectroscopy from orbit have proved inconclusive (Lane and Christensen, 1998; e.g., Bandfield, 2002). While lander missions provide reliable measurements of Cl at specific locations, these measurements cover an extremely limited geographical area of the planet surface. Observations made using the Gamma Subsystem of the Gamma Ray Spectrometer (GRS) instrument suite aboard the 2001 Mars Odyssey spacecraft (Boynton et al., 2004; Boynton et al., 2007) indicate that the distribution of Cl is heterogeneous across the planet. GRS detects gamma ray photons emitted within the upper few tens of centimeters of the surface of the planet. Thus, in addition to providing the first global measurement of Cl, GRS is sensitive to surface compositions at depths exceeding the reaches of infrared and visible remote-sensing instruments. Geographically distinct regions show varying concentrations of Cl, some of which may be linked to regions previously mapped based upon surface morphology. We are also able to identify relationships between Cl and the abundances of other elements and physical parameters. These results are described below along with hypotheses regarding geologic surface processes that may account for the global distribution of Cl observed by GRS.

5.4 Methods

5.4.1 Data Processing

For complete details regarding collection and processing associated with the GRS data presented here, see Boynton et al. (2007). Gamma ray spectra were collected every 19.75 seconds as the Mars Odyssey spacecraft orbited Mars from 8 June 2002 to 2 April 2005. Concentrations have been determined for the elements K, Th, H, Si, Fe, and Cl based upon gamma rays from the martian surface collected during this time period (Boynton et al., 2007).

Gamma rays from non-radioactive elements result from inelastic scatter and capture interactions with neutrons released through bombardment by high-energy cosmic ray particles at the surface of Mars (Reedy, 1978; Boynton et al., 1992; Rao et al., 2002; Boynton et al., 2004). In the case of Cl, gamma rays result from neutron capture. While neutrons of any energy can be captured, the capture cross-section for lower energy thermal neutrons tends to dominate. Consequently, the production of Cl gamma rays is highly dependent on the flux of thermal neutrons near the surface, which can be significantly affected by composition. For example, hydrogen near the surface will both slow neutrons to thermal energies and absorb thermal neutrons. A capture correction factor has been applied to the Cl data to account for variations in the thermal neutron flux. This correction factor is based upon the ratio of gamma ray fluxes produced by Si both from neutron capture and inelastic scatter events (Si-capture / Si-scatter) as a proxy for the thermal neutron environment at the surface (Boynton et al., 2007).

While this approach appears to provide reasonable results in the equatorial and mid-latitudes, the presence of large amounts of water ice buried near the surface towards high latitudes makes the correction technique less effective due to both the strong influence of H on neutron flux and the effects of layering at the surface. We constrain the results presented here using a regional cut-off mask based upon water-equivalent hydrogen concentration as described and illustrated by Boynton et al. (2007), hereafter referred to as the water-correction mask. The Cl data used in this analysis are from equatorial and mid-latitude regions of the planet (the water-correction mask excludes data poleward of ~50º latitude in both hemispheres).

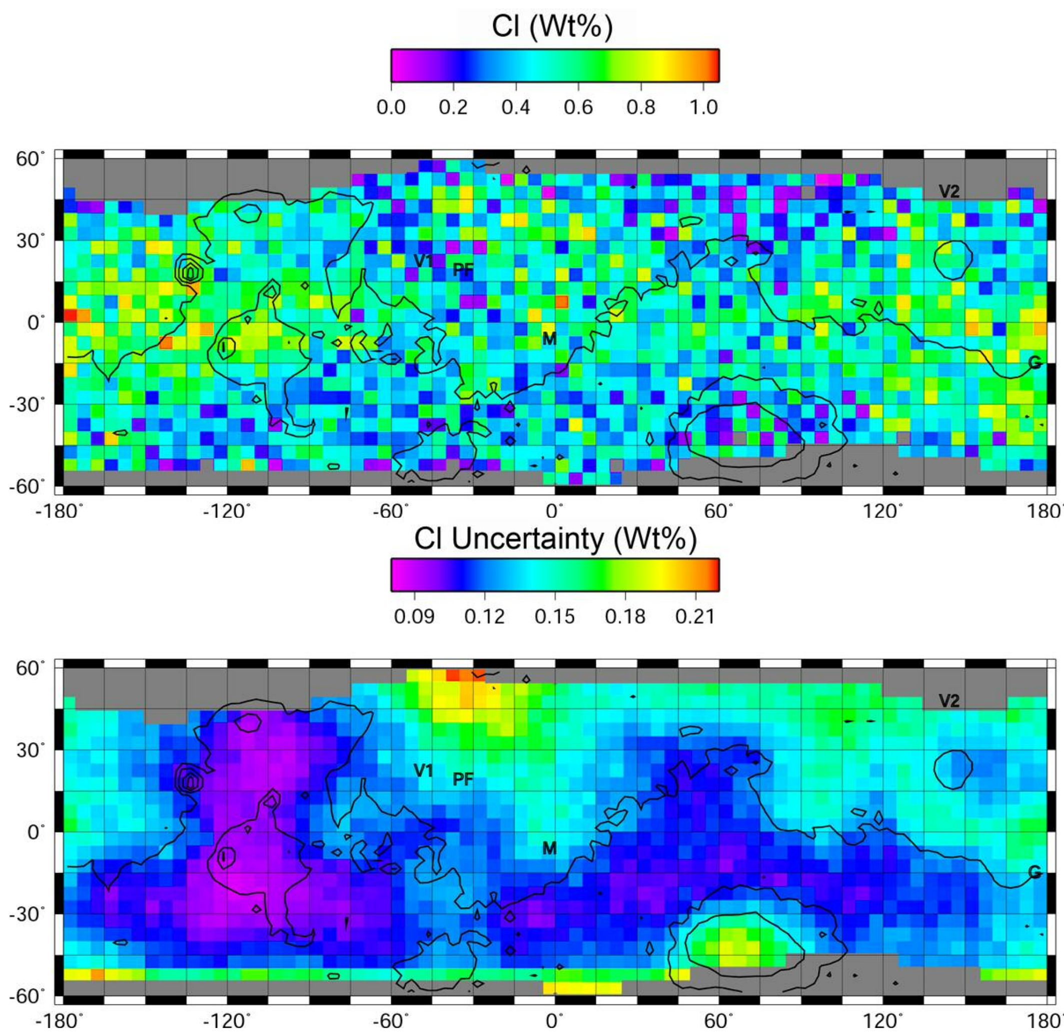
Analysis of the full martian gamma ray spectrum reveals more than 20 peaks associated with Cl (including escape peaks created by incoming gamma rays through particle interactions within the detector) (Evans et al., 2007). Chlorine concentration reported here is the sigma-weighted mean of concentrations determined from 5 of these peaks, centered at 1951, 1959, 6111, 5600 (the first escape peak of 6111), and 7790 keV. These peaks have high signal to noise ratios (S/N), have well known cross sections, and stand out clearly above the continuum. Peak areas determined from spectral sums are 1) corrected for the gamma ray background, atmospheric attenuation, and detector efficiency, 2) compared with counts predicted by a neutron and gamma ray transport code to determine a concentration value at the surface, and 3) corrected for variations in the thermal neutron environment using the correction factor based upon Si described above (Boynton et al., 2007).

Mean Cl concentrations are determined either for increments of latitude and longitude, called bins, or for irregularly shaped user-defined areas, called regions. The uncertainty of the mean, s_m, is estimated for each bin or region based upon the 1σ error associated with peak areas measured during spectral peak fitting for that location. Because coarser bins (e.g., 10-x-10º bins) yield higher gamma ray photon counts, these will have higher S/N and smaller uncertainty values than finer bins (e.g., 2-x-2º bins). Similarly, larger regions will have higher S/N and smaller s_m values than smaller regions.

Adjustments are made to uncertainty values to reflect all corrections applied during data processing.

The Cl concentration and corresponding s_m value for each 5-x-5° bin are presented in Figures 5-1a and 5-1b, respectively. The area-weighted mean concentration for the bins shown is 0.49 wt% Cl, with concentration values ranging to a maximum of 1.04 wt% Cl. As the 5-km contour lines in Figure 5-1b show, lower elevation regions (e.g., Hellas) typically have higher uncertainties due to greater atmospheric attenuation of the gamma ray signal. The average instrumental uncertainty (s_{rms}) for the binned dataset, computed as the root-mean-square of the s_m values of all 5-x-5° bins within the water-correction mask, is 0.13 wt% Cl. While the dataset is noisy, the concentration of Cl varies spatially in a statistically significant manner across the planet, and broad clustered regions of higher and lower Cl concentration are evident.

Figure 5-1 Map of unsmoothed 5º-x-5º chlorine data



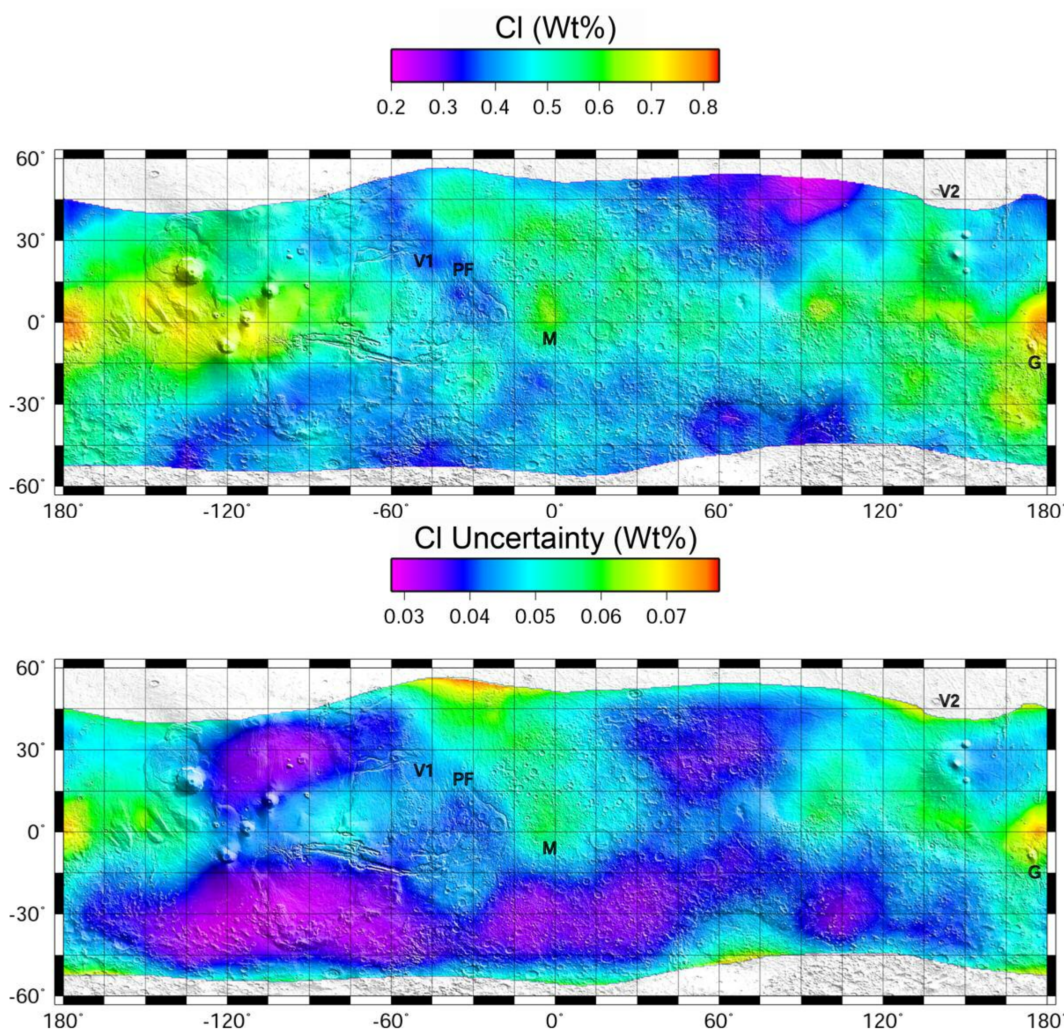
Binned 5-x-5° Cl gamma ray data before smoothing. a) Corrected Cl concentration values. See text for description of data processing. Data has been masked to remove high latitude regions where large amounts of buried water ice make it difficult to obtain reliable concentration estimates. Locations of landing sites are labeled, and contour lines show 5-km elevation levels on the planet. This figure reveals the resolution and quality of GRS data before smoothing. The scale bar used excludes 9 bins with negative values measured within the instrumental uncertainty of the dataset. b) Corrected uncertainty values. Values represent the uncertainty of the mean (sm) for each 5-x-5° bin based upon the 1σ error associated with peak area obtained from the gamma ray spectral sum and corrections for the thermal neutron flux based upon Si. Note that uncertainty is anti-correlated with elevation due to effects of atmospheric attenuation.

5.4.2 GRS Footprint, Data Smoothing, and Mapping

The GRS detector is a non-directional detector that senses gamma rays from a large footprint on the surface of Mars. However, due to atmospheric attenuation of gamma rays, the probability of detection falls off with increasing angular distance away from nadir. As discussed by Boynton et al. (2004; 2007), the GRS footprint varies with energy: 50% of the detected signal comes from a circular area with a diameter of ~440 km for the low energy Cl peaks (around 1950 keV) and ~540 km for high energy Cl peaks (up to 7790 keV). These footprint sizes range from 7-9º of arc in diameter at the planet surface.

Because of low counting statistics associated with 5-x-5º binned Cl data, smoothing has been applied to data provided in Figure 5-1. Figure 5-2a shows the results of rebinning the 5-x-5º Cl data to 0.5-x-0.5˚ cells and smoothing with a 10˚-arc-radius boxcar mean filter. Figure 5-2b shows a reduction in the instrumental uncertainties compared to the unsmoothed instrumental uncertainties in Figure 5-1b.

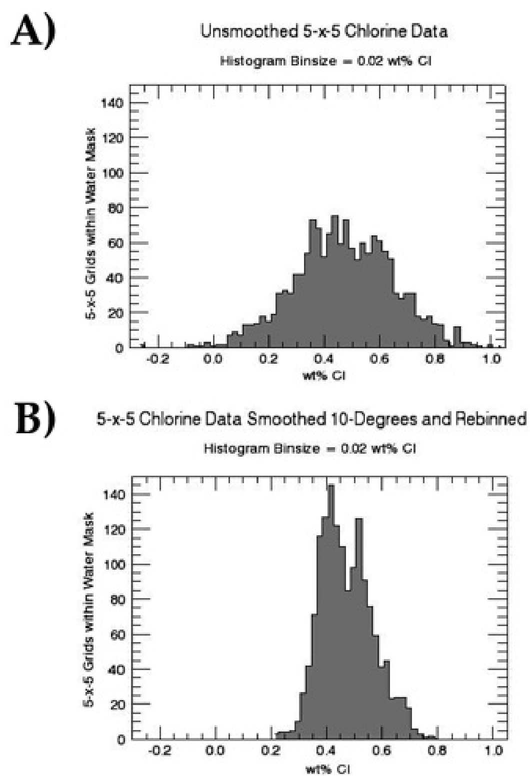
Figure 5-2 Map of 5º-x-5º chlorine data smoothed 10-degrees



Binned 5-x-5° Cl gamma ray data after smoothing. a) Corrected and smoothed Cl concentration values. Masked 5-x-5° data shown in Figure 1a has been rebinned to 0.5-x-0.5° cells and smoothed with a 10º-arc-radius boxcar mean filter. Locations of landing sites are labeled and MOLA elevation data is shown in shaded relief. b) Masked 5-x-5° uncertainty data (sm) shown in Figure 1b has been rebinned to 0.5-x-0.5° cells and smoothed with a 10º-arc-radius boxcar mean filter treating uncertainty values appropriately. Anti-correlation with elevation due to atmospheric attenuation of gamma ray signal is still evident. While data smoothing increases numerical precision, it reduces both spatial certainty and the range of reported concentration values.

While numerical uncertainty is reduced through smoothing, spatial certainty is decreased because the smoothing filter is larger than the 7-9˚ diameter GRS 50% footprint (Boynton et al., 2007). As shown in histograms of the unsmoothed and smoothed data in Figures 5-3a and 5-3b, smoothing decreases the range of concentration to 0.22~0.80 wt% Cl by averaging random fluctuations. Smoothing also reduces s_{rms} to 0.05 wt% Cl for the data rebinned to 5-x-5º, while the area-weighted mean concentration remains 0.49 wt% Cl.

Figure 5-3 Histograms of 5º-x-5º chlorine data



Histograms of concentration for masked Cl 5-x-5° dataset. a) Histogram for unsmoothed masked 5-x-5° dataset shown in Figure 1a using histogram bin size of 0.02 wt% Cl. b) Histogram for masked 5-x-5° smoothed and rebinned data shown in Figure 2a using histogram bin size of 0.02 wt% Cl. Notice decrease in range of Cl concentration values due to data smoothing.

With or without smoothing, the estimated Cl concentration at any given location is influenced by the composition in surrounding areas. A comparison between GRS data and measurements made at landing sites shows this effect. Table 5-1 provides estimates of mean Cl abundances for four of the landing sites based upon material densities, rock abundances (Christensen, 1986; Christensen and Moore, 1992), compositions (Clark et al., 1982; Wänke et al., 2001; Gellert et al., 2004; Rieder et al., 2004; Gellert et al., 2006), and GRS water-equivalent hydrogen estimates (Boynton et al., 2007) for each site. See Karunatillake et al (2007a) for detailed description of landing site composition estimates.

Table 5.1 Lander site estimates for GRS chlorine detection

Lander	Lander Cl Wt%	GRS Cl Wt% Unsmoothed (Fig 5-1)	GRS Cl Wt% Smoothed (Fig 5-2)
Pathfinder (Ares Vallis)	0.49 +/- 0.07	0.24 +/- 0.13	0.37 +/- 0.04
Viking 1 (Chryse Planitia)	0.71 +/- 0.17	0.36 +/- 0.14	0.37 +/- 0.04
Spirit (Gusev Crater)	0.69 +/- 0.04	0.65 +/- 0.14	0.68 +/- 0.06
Opportunity (Meridiani Planum)	0.54 +/- 0.03	0.61 +/- 0.15	0.59 +/- 0.06

Comparison of predicted Cl concentration for each landing site (based upon lander and remote sensing determinations of soil composition[Clark et al., 1982; Gellert et al., 2004; Rieder et al., 2004; Wänke et al., 2001], rock composition [Gellert et al., 2004; Wänke et al., 2001], rock abundance [Christensen, 1986b], water-equivalent hydrogen [Boynton et al., 2006], and density [Christensen and Moore, 1992]) with measured GRS values obtained for both unsmoothed 5-x-5° data and data smoothed with a 10º-arc-radius boxcar filter. See Karunatillake et al. (2007a) for futher details. Discrepancies between lander predictions and GRS values are most likely due to geochemical diversity within the large GRS footprint and 10º-arc-radius boxcar smoothing circle, both of which are much larger than lander sample field sizes.

Corresponding GRS data for Cl, both smoothed and unsmoothed, are also provided. The discrepancies shown between lander and GRS values are likely related to the difference in size between the GRS footprint and lander sample ranges. While both Spirit and Opportunity have traveled several kilometers, these distances are insignificant compared to the size of the GRS footprint. Thus, GRS Cl data presented here should be interpreted as reflecting variations in Cl over scales significantly larger than the 5º summing and 10º-arc-radius smoothing that has been applied.

5.4.3 Effects of Material Mixing Geometry

As described by Squyres and Evans (1992), the material mixing geometry of rocks and soils has an effect on the energy distribution of neutrons and production of gamma rays. For each bin, our data processing procedure assumes a homogeneous thermal neutron flux at the surface as determined by measurements of Si gamma rays from both capture and scatter events (Boynton et al., 2007). For the Cl analysis presented here, there is uncertainty associated with this assumption. A non-homogenous thermal neutron flux caused by shielding within basaltic rocks larger than the neutron mean free path of a few centimeters will have a greater effect on Si gamma rays than on Cl gamma rays coming from these Si-rich, Cl-poor materials.

To better understand the effects that material mixing may play in our concentration estimates, we have modeled the expected flux of gamma rays from Si-capture and Si-scatter events in both soil and rocks using a neutron and gamma ray transport code. Using a model which assumes a Pathfinder composition soil material (with 3% water-equivalent hydrogen and 0.55 wt% Cl) and an extreme case of large rocks essentially free of both H and Cl (0.011 wt% for each), we find that the ratio of Si-capture to Si-scatter gamma rays for the rock material is lower than for the soil material because of a decreased thermal neutron flux in the rock. This is due to the absence of H in the dryer rock material and the fact that H is efficient at moderating neutrons to thermal energies in the soil material. Dividing the correction factor (Si-capture / Si-scatter) obtained for rock by the correction factor for soil leads to a value of 0.826. Because we divide the Cl gamma ray flux coming predominantly from the soil by the correction factor that is affected by both rocks and soil, our current data processing methodology may overestimate the Cl concentration in regions with a substantial number of rocks greater than a few centimeters in size. If we assume an upper limit for rock abundance of 35% in a given sampling area (Christensen, 1986), this indicates that we may be overestimating the Cl concentration in some regions by roughly 6%. While both additional modeling of material mixing effects (Kim et al., 2006) and data constraining the actual nature of material mixing across the martian surface are required to treat this problem more rigorously, potential overestimates of regional Cl concentration values reported here appear to be small.

5.5 Chlorine Results

The preceding section outlines data processing and mapping techniques used to obtain the binned compositional data presented here. Attention to detail has been applied to the complex challenge of converting measured gamma rays detected in orbit to Cl concentrations and uncertainty values at the surface of Mars. Due to certain limitations, including the large footprint of the GRS instrument, low S/N, and weak constraints on the surface thermal neutron flux (Boynton et al., 2007), it is important to avoid the temptation to use GRS data to analyze concentration values at distinct locations on the planet smaller than roughly 20º in diameter at the equator. As seen in Figures 5-1 and 5-2, the GRS data provide insight into the distribution of Cl on Mars that can be used to guide consideration of processes that would affect the distribution of Cl on Mars at these large scales. Significant variations in Cl seen at scales greater than 20º are real and likely related to surface processes that have occurred or are now occurring on the planet. Key observations for Cl are described in this section followed by a discussion that considers probable geologic mechanisms responsible for the distribution of Cl on Mars.

5.5.1 Enriched Surface Cl Abundance

Analyses of a grand sum of all spectra collected within the water-correction mask result in a global mean value of 0.49 wt% Cl with an uncertainty of the mean (sm) of 0.03 wt% Cl. Because spectra from across the planet have been summed together, this represents our most numerically precise determination of the global mean concentration excluding high latitude regions, but lacks spatial information. The same global mean value of 0.49 wt% Cl is determined using 5-x-5º bin data (see Section 5.4.1 and 5.4.2), which also provides the opportunity to investigate spatial variation across the planet discussed below.

The GRS global Cl average is consistent with lander measurements described in the introduction and a mean estimate of ~0.3 wt% Cl determined by Rao et al. (2002) using excesses found in martian meteorites of isotopes generated through neutron capture interactions with Cl and Br. These values are all substantially higher than current estimates of 0.015-0.032 wt% for the elemental abundance of Cl in the martian mantle and crust (Lodders and Fegley, 1997; Rao et al., 2005) and values for Cl found in the SNC meteorites from Mars (0.0014-0.11 wt%) (Banin et al., 1992). Secondary surface processes that are likely to be responsible for this enrichment of Cl are presented in the discussion section.

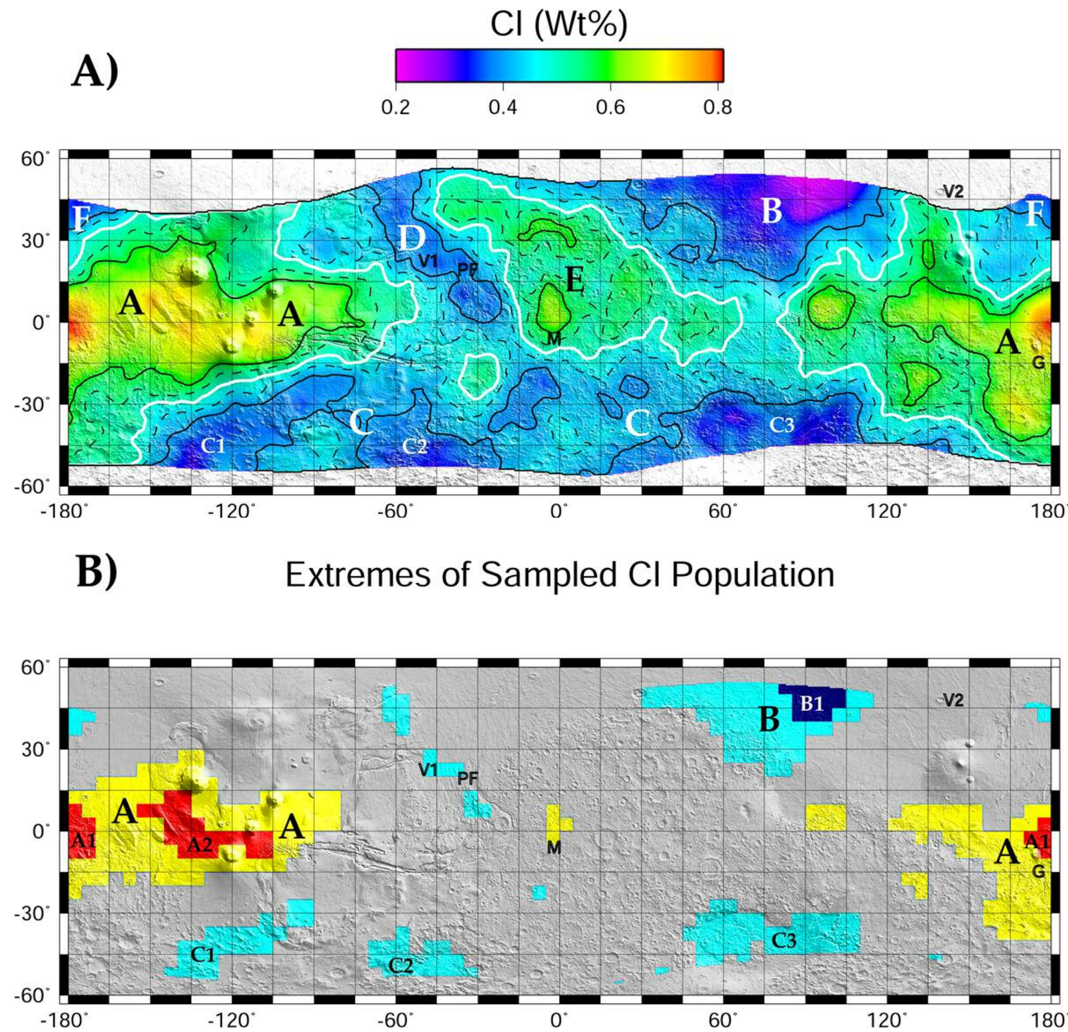
5.5.2 Heterogeneous Cl Distribution on the Martian Surface

As shown in Figures 5-1 and 5-2, the distribution of Cl is heterogeneous across the surface of Mars. In the unsmoothed dataset, values range to a maximum of 1.04 wt% Cl with an average instrumental uncertainty (s_{rms}) of 0.13 wt% (see Section 5.4.1 above). In the smoothed and rebinned dataset, Cl varies by a factor of ~4, from 0.22~0.80 wt% Cl, across geographically large regions of high and low Cl, with an average instrumental uncertainty (s_{rms}) of 0.05 wt%. Because smoothing reduces the range of reported values, this factor of ~4 represents a lower estimate of variation in Cl concentration across the globe and points to substantial and real differences over the martian surface. Histograms (Figure 5-3) show the distribution of Cl values for both unsmoothed and smoothed 5-x-5° data. To further characterize the dispersion of the Cl values reported over the planet, we find the standard deviations of both unsmoothed and smoothed 5-x-5° bins to be 0.18 and 0.10 wt% Cl, respectively. The standard deviation (s), computed from the variation of bin values around the mean value, is influenced by both instrumental uncertainty and actual geospatial variation within a sample. Because the standard deviation values exceed the corresponding s_{rms} measurements of instrumental uncertainty, we believe that the spatial variations described below represent actual surficial geochemical diversity on Mars.

The GRS instrument is sensitive to compositions within the upper few tens of centimeters of the martian surface. Thus, variation in Cl concentration may also reflect three dimensional differences. GRS provides the first geochemical remote sensing information deeper than a few micrometers. The intricate issues regarding GRS sensitivity to layering of surface materials are saved for future work (e.g., Keller et al., 2006); however, it is important to note that some of the variation in Cl seen in Figures 5-1 and 5-2 may be caused by compositional differences at depth.

To highlight the distribution of Cl, Figure 5-4a shows contour lines drawn at the global mean value of 0.49 wt% Cl (solid white contour) and at values 0.05 wt% (dashed black contour at 1 s_{rms}) and 0.10 wt% (solid black contour at 2 s_{rms}) from this global mean. Because s_{rms} represents an average instrumental uncertainty for 5-x-5° binned data, the black solid contour lines characterize regions with Cl concentrations that are detectably above and below the global mean Cl value. Several large contiguous regions have been labeled for reference purposes and are discussed at further length throughout the paper.

Figure 5-4 Map of high and low chlorine regions



Analyses for highlighting high and low Cl regions. a) White contour shows areas on planet with global mean Cl concentration value of 0.49 wt%. Black contours show locations with values 0.05 wt% (dashed contour at 1srms) and 0.10 wt% (black solid contour at 2srms) above and below the global mean value. The srms uncertainty was used. b) Results of statistical analyses to identify bins at the extreme ends of the Cl population distribution. Using smoothed data rebinned to 5-x-5º, concentration and sm uncertainty values for each bin were compared to the global arithmetic mean and standard deviation (s) using a Student's t-test. Bins significantly below the global mean are shown in light blue (1s) and dark blue (2s). Bins significantly above the global mean are shown in yellow (1s) and red (2s).

To further characterize high and low Cl concentration values and account for geospatial variation within the population sampled by GRS, we have rebinned the smoothed data presented in Figure 5-4a back into 5-x-5º bins. For each of these, we examined the probability that the datum could have been obtained from sampling a random normal parent population with 1508 data points (the total number of masked 5-x-5º Cl data points obtained after rebinning). Measured data with values significantly above or below the global mean have a lower probability of being randomly sampled and are more likely to be located in the wings of the parent population. We applied a two-tailed Student's t-test on each datum. The test utilized 1506 degrees of freedom with the test parameter, t, for the ith bin computed as:

$$t_i = \frac{m_g - m_i}{\sqrt{(s_m)_i^{\,2} + s^2}}$$

where mg is the global arithmetic mean wt%, mi the wt% at the bin location, (sm)i the instrumental uncertainty of mi, and s the standard deviation as an estimate of the population standard deviation (σ). The term $(s_m)_i$ ensures that bins with high instrumental uncertainty are given less significance for deviating from the global mean. We have also verified that the global distribution of Cl is roughly random normal and that mg and s are minimally affected by spatial autocorrelation issues (e.g., Haining, 2003). Consequently, the t-test is a statistically meaningful way to quantitatively highlight the spatial variability of Cl. The results of this analysis are presented in Figure 5-4b. Data points less than 32% probable of being randomly sampled from the parent population (i.e., displaced more than 1*s* from the mean) and less than 5% probable (2*s*) are shown. Regions located in the low Cl wing of the population distribution are colored light blue (1*s*) and dark blue (2*s*). Highlighted regions in the high Cl wing are shown in yellow (1*s*) and red (2*s*). Interestingly, we find that 26% of the bins pass the t-test at the 1*s* -level and 3% pass at the 2*s* -level. These results agree with expectations that 32% and 5% of the population are found 1σ and 2σ, respectively, away from the mean of a random normal population distribution. Because these bins cluster into contiguous regions, we regard these to be geochemically significant regions of distinctly high and low Cl content relative to average Mars. For each labeled region in Figure 5-4b, we have also summed all gamma ray spectra collected over that region to obtain a mean concentration value and uncertainty of the mean (s_m) listed in Table 5-2.

Table 5.2 Chlorine values for high and low Cl regions

Region	Mean Concentration (wt% Cl)	Uncertainty of Mean (wt% Cl)
Global Value	0.49	0.03
A – 1*s* outlier	0.67	0.04
A1 – 2*s* outlier	0.81	0.07
A2 – 2*s* outlier	0.73	0.05
B – 1*s* outlier	0.31	0.03
B1 – 2*s* outlier	0.22	0.05
C1 – 1*s* outlier	0.34	0.03
C2 – 1*s* outlier	0.38	0.04
C3 – 1*s* outlier	0.36	0.03

We also provide descriptions and geographic context (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka et al., 1992; Dohm et al., 2005) for regions of high and low Cl highlighted in Figures 5-4a and 5-4b. A region of significant Cl enrichment is located along the equator of Mars that includes and extends predominantly west of the giant shield volcanoes of Tharsis Montes (Figures 5-4a and 5-4b, Region A). This region contains the highest Cl values on the planet, with a maximum value of 0.80 wt% Cl after smoothing with a 10°-arc-radius mean filter and rebinning to 5°. The region encompasses the Medusae Fossae Formation (MFF) along the highland-lowland boundary west of Tharsis Montes. The high Cl region also extends east of Tharsis Montes, north to include Olympus Mons and parts of Amazonis Planitia, south of Gusev Crater into Terra Cimmeria, and west into Elysium Planitia. Two large continuous areas contained within the region have values associated with the high 2*s*-wing of the Cl population (Figure 5-4b). Region A1 is centered over Memnonia Sulci, which has been mapped as a rougher, deeply eroded middle member of MFF. To the east, Region A2 encompasses both MFF materials south of Olympus Mons and lava flows associated with Tharsis Montes.

The triangular-shaped region with low Cl in the northern hemisphere (Figures 5-4a and 5-4b, Region B) extends north of Syrtis Major into Utopia Planitia and Vastitas Borealis. Shown in Figure 5-4b, Region B1 contains the minimum global Cl value of 0.22 wt% Cl and is located over the mottled, grooved, and knobby members of the Vastitas Borealis Formation. A second region of low Cl in the northern hemisphere is shown in Figure 5-4a extending from the southeast to the northwest through Chryse Planitia and Tempe Terra (Figure 5-4a, Region D). While this region does not definitively occupy the low concentration wing of the Cl population represented in Figure 5-4b, the 15-x-75º strip shown in Figure 5-4a is a continuous region with measurably lower Cl values than the global Cl concentration based upon s_{rms}, a measure of instrumental uncertainty.

Apart from the southern extension of Region A into Terra Cimmeria, we find that the majority of the southern mid-latitudes have moderately low Cl concentrations (Figure 5-4a, Region C). Three smaller southern hemisphere regions that lie within the low 1*s* -wing of the Cl population are highlighted in Figure 5-4b. These include an area east of Terra Sirenum (Region C-1), a region including and to the west of Argyre Planitia (Region C-2), and a section spanning from Hellas Planitia to Promethei Terra (Region C-3). As shown in Figure 5-4a, the Cl values in the southern highlands are generally lower than the mean global Cl concentration.

Similar to Region D, two additional regions detectably diverge from the global mean (Figure 5-4a) but do not occupy the extremes of the Cl population (Figure 5-4b). Moderately elevated Cl concentrations are found in a broad area centered over Arabia Terra (Figure 5-4a, Region E) surrounded by the lower values of Regions B, C, and D. Moderately low values are found east of the Elysium volcanic rise extending into Arcadia Planitia (Figure 5-4a, Region F). Because Figure 5-4a is based upon instrumental uncertainty (s_{rms}), these regions are measurably higher and lower than the global mean concentration. However, only small portions of each region are found to be within the 1*s*-wings of the Cl population (shown in Figure 5-4b), and the regions do not represent areas of extreme enrichment or depletion.

Finally, Figure 5-4a shows transitions between the high and low Cl regions that are both sharp and narrow in some places (e.g., between Regions A and C-1) and broad and less clearly defined in other areas on the planet (e.g., between Regions A and C-3). Due to the large footprint of GRS and smoothing of the dataset, the Cl concentrations reported in these transitional regions could either result from straddling distinct regions of high and low Cl concentrations (more likely for sharp, narrow transitions) or reflect a true gradient in concentration (more likely for broad intermediate regions). Any number of non-unique solutions at scales smaller than the GRS footprint could account for the actual GRS measurements reported here.

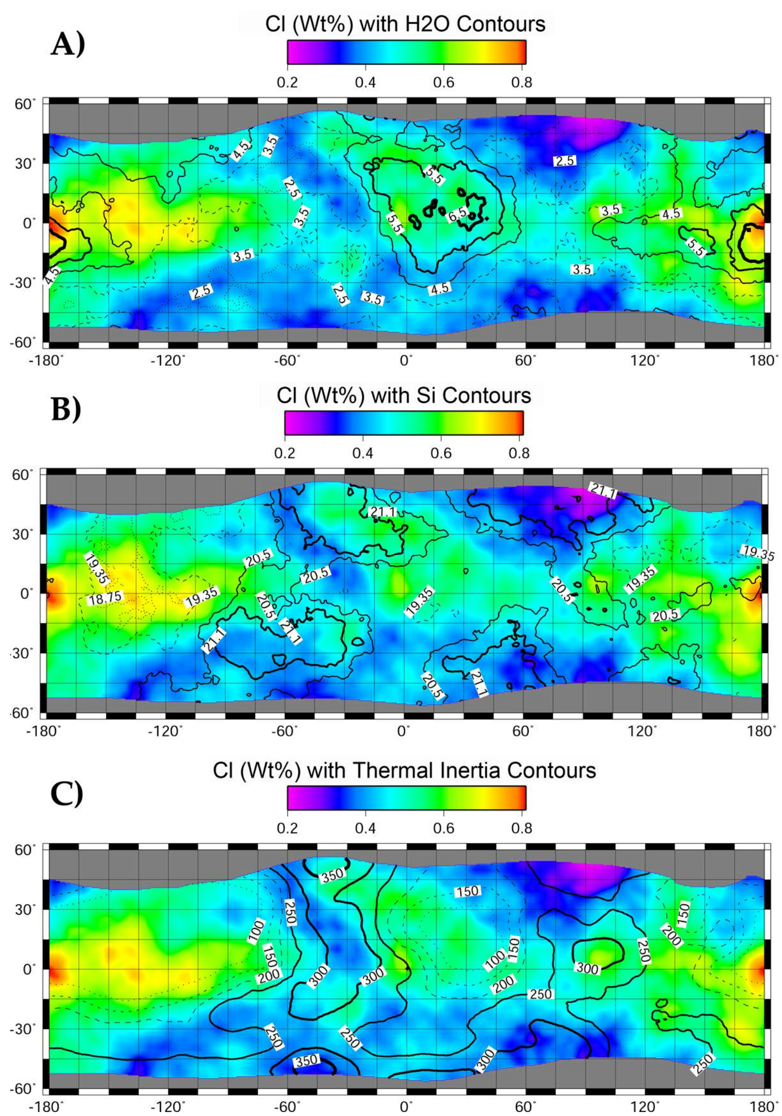
5.5.3 Correlation of Cl with H, Si, and Thermal Inertia

We have also applied statistical analyses to reveal spatial correlations of Cl with other elements (H, Fe, Si, K, and Th) and physical parameters (thermal inertia, albedo, rock abundance, and Surface Type 1 and 2 areal abundances) in the equatorial and mid-latitudes. Elemental concentrations were smoothed with a 10º-arc-radius boxcar mean filter as described by Boynton et al. (2007). Physical data were obtained from work by Christensen and Malin (1988), Christensen (1988), Christensen (1986), and Bandfield et al. (2000). As described by Karunatillake et al. (2007b), hierarchical modeling utilized statistical significance estimates from three different linear multivariate regression methods (least squares, spatial autocorrelation, and measurement error) to determine the most significant parameters for the spatial distribution of Cl.

In models consisting solely of elemental parameters, H and Si were the most significant and accounted for ~40% of the variability in Cl. In comparison, among models containing only physical parameters, thermal inertia, rock abundance, and Surface Type 2 (ST2) accounted for only ~30% of the variability. Furthermore, physical parameters varied in importance across the three regression methods. This suggests tentatively that, of the parameters analyzed, H and Si may be the most significantly involved in the variability of Cl. While additional hierarchical modeling with all five strongest parameters (H, Si, thermal inertia, rock abundance, and ST2) did not significantly favor any given set of reduced parameters, the model with only H, Si, and thermal inertia was marginally better than other combinations. Furthermore, in the presence of H, Si, and thermal inertia, the parameters of rock abundance and ST2 were not consistently significant at 95% confidence, indicating they may be redundant. Therefore, our final hierarchical model consists of H, Si, and thermal inertia. Figure 5-5 shows the spatial relationship between these parameters and Cl by overlaying contours of H, Si, and thermal inertia on top of the Cl map. Pairwise scatter plots for these parameters with Cl are shown in Figure 5-6. A positive correlation exists between Cl and H with a partial correlation coefficient of +0.2. Negative correlations with Cl were found for both Si and thermal inertia, with partial correlation coefficients of -0.2 and -0.1, respectively. Together, these three parameters account for ~40% of the variation seen in the Cl dataset (R^2=0.4). Our analyses do not establish causal relationships but show that of the ten parameters considered, global spatial associations for Cl are strongest with H, Si, and thermal inertia, listed in proposed order of importance.

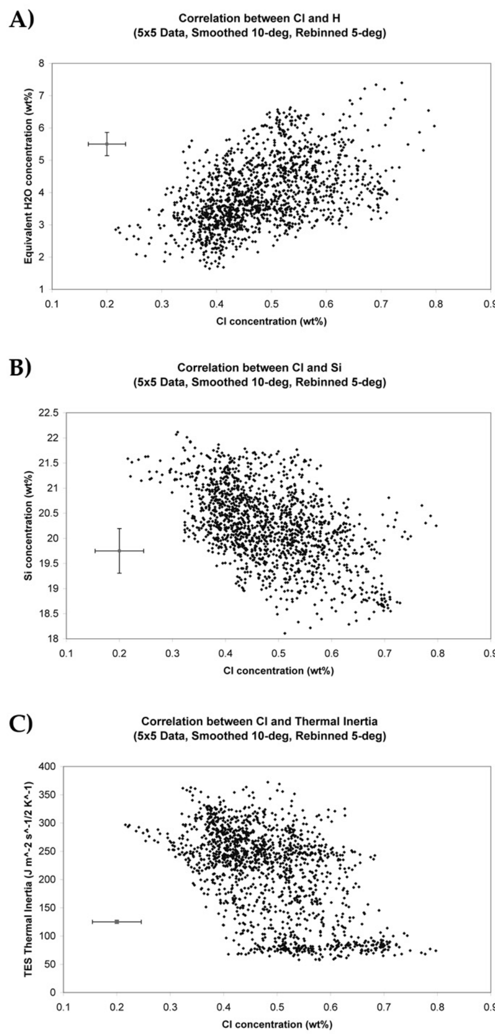
While the data used in these analyses have been smoothed, corrected, and rebinned, it is important to note that the correlations are not data reduction artifacts associated with correction factors described in Section 5.4.1 and by Boynton et al. (2007). We investigated this possibility by comparing elemental correlations both before and after corrections were applied. The positive correlation between Cl and H is present in both datasets with comparable partial correlation coefficients. This result is not surprising given that the same capture correction is applied to both elements. The negative correlation with Si is actually stronger in the uncorrected data, and the capture correction applied to Cl and scatter correction applied to Si (Boynton et al., 2007) significantly reduce the partial correlation coefficient to the value reported above. Based upon known effects of H and Fe on the energy distribution of near-surface neutrons, we feel confident that correction factors are necessary and are not artificially enhancing the correlations identified above. The net spatial autocorrelation effects associated with smoothing, rebinning, and spacecraft footprint are more difficult to assess. However, as a practical measure, we assumed that severe spatial autocorrelation does not extend beyond the 10°-arc-radius smoothing filter. Through the use of spatial autocorrelation analysis in our regression methods, we have attempted to adjust the partial correlation coefficients reported here for the presence of spatial autocorrelation. Future work will incorporate exact estimation of the spatial scale of isotropic spatial autocorrelation for each elemental dataset (Haining, 2003).

Figure 5-5 Maps showing correlations of Cl with H, Si, and thermal inertia



Maps showing spatial relationships between Cl and parameters of water-equivalent hydrogen, Si, and thermal inertia. All three figures show false-color maps of smoothed Cl data overlain with contours of non-Cl parameters. a) Contour overlay of water-equivalent hydrogen shows positive correlation between Cl and H. b) Contour overlay of Si shows negative correlation between Cl and Si, with regions of low Cl corresponding to regions of high Si. c) Contour overlay of thermal inertia. Negative correlation with thermal inertia dominated by high Cl values enclosed by region of low thermal inertia around Amazonis between -75 and 165E longitude. Note that this region of low thermal inertia extends significantly north of the region of high Cl centered over Medusae Fossae.

Figure 5-6 Pairwise correlation plots of Cl with H, Si, and thermal inertia



Pairwise correlation plots comparing Cl with water-equivalent hydrogen, Si, and thermal inertia. Elemental values for Cl, Si, and water-equivalent hydrogen were determined from 5-x-5° binned GRS data; thermal inertia is based upon TES measurements. All data has been smoothed with 10º-arc-radius boxcar mean filter and rebinned to 5-x-5° bins. Also shown are average instrumental uncertainty values (srms) obtained from all points plotted. Evident in the plots are a positive correlation of Cl with H_2O and negative correlations of Cl with Si and with thermal inertia. See text for description of hierarchical multivariate correlation analyses using several different linear multivariate regression methods regarding associations of Cl with these and other elemental and physical parameters.

5.6 Discussion

The discovery of spatial variation in Cl has significant implications for our understanding of the geologic history of Mars and processes that have modified its surface. We consider four primary working hypotheses (aeolian, volcanic, aqueous, and hydrothermal) that may collectively explain the distribution of Cl detected by GRS. The GRS data do not exclude any one mechanism, and the relative importance of each may vary from region to region. In particular, while variations in both the aerial extent and depth of dust at the surface may be contributing somewhat to the Cl signature, it does not appear to explain all of the variation observed. We propose that Cl enrichment centered over the Medusae Fossae Formation (Figure 5-4, Region A) may have resulted from reactions with acid-fog or acidic precipitation related to volcanic exhalations within or upwind from this region. However, we cannot rule out that chemical alteration through hydrothermal activity in the area may have affected the Cl distribution as well. Dependent on both the water history of the planet and regional variations in soil porosity, leaching and transport of Cl by liquid water also have likely influenced Cl concentrations within the upper few tens of centimeters in different regions. Cl enrichment through evaporitic processes may account for elevated Cl signature in some regions. The Cl signature currently found on the martian surface likely reflects a complex and interesting history that remains to be unraveled.

5.6.1 Hypothesis 1: Aeolian Deposition of Cl-Rich Dust

Based primarily on physical properties, Viking mission scientists identified three primary categories of surface materials: rocks, soil, and drift material (Moore et al., 1987;

Christensen and Moore, 1992). Chemical analyses for soil and drift components by Viking, Pathfinder, and MER show remarkable similarities in composition (especially in Si, Fe, Mg, and Al) for soil and drift components, and it has been proposed that this may result from mixing of local rock with a more homogeneous global fine component (e.g., Clark et al., 1982; Wänke et al., 2001; Gellert et al., 2004; Rieder et al., 2004). Yen et al. (2005) noted that two fine components found at both MER landing sites ("bright dust" immediately at the surface and "dark soils" with lower sulfur content) show strong compositional uniformity within each group. These components are compositionally more similar at all five lander sites than they are to local source rocks, indicating that both components have likely been delivered through aeolian processes or derived from similar rocks. Measured Cl concentrations in the soil and dust components vary from 0.3 to 1.2 wt% and are higher than concentrations found for measured basaltic rocks (Wänke et al., 2001; Gellert et al., 2004; Rieder et al., 2004; Yen et al., 2005; Gellert et al., 2006).

Because GRS is sensitive to composition within the upper few tens of centimeters of the surface, one possible explanation regarding the global distribution of Cl is that GRS is detecting regions with varying thicknesses of globally-mixed dust and soil that is rich in Cl. It is has been reported that the Tharsis and Amazonis regions of Mars are sites of active dust deposition under current climate conditions (Christensen, 1986), with thickness estimates ranging from a few centimeters (based upon the thermal skin depth of infrared wavelengths used to measure thermal inertia) to a few meters (based upon radar reflectivity of the surface and estimates of rock abundance) (Christensen, 1986; Christensen, 1986). Based upon analyses of MOC images and other lines of evidence, regions of meter-thick mantling of potential airborne origin within Amazonis, Tharsis, and Arabia have also been proposed (Newsom et al., 2007). GRS may be detecting thick deposits of Cl-rich dust in Region A of Figure 5-4. In the low Cl regions north of Syrtis Major and in the southern highlands (Regions B and C), the signal from the Cl-rich fine component may be diluted by mixing with Cl-poor rocks.

As described in Section 5.5.3, we have looked for spatial correlations of Cl with parameters of thermal inertia, albedo, rock abundance, and TES mineralogy, all of which serve as potential indicators for dust and soil components versus rocky materials. Dusty regions have been proposed for areas with lower thermal inertia and higher albedo (Christensen, 1986; Christensen, 1986; Mellon et al., 2000; Putzig et al., 2005). Negative correlations between Cl and thermal inertia and Cl (see Figure 5-6c) and rock abundance and a positive correlation between Cl and albedo are consistent with the hypothesis that low thermal inertia mobile fine materials are enriched in Cl. Figure 5-5c provides a spatial comparison between Cl and thermal inertia (contour lines). It is evident from the figure that the high Cl region west of Tharsis centered over Medusae Fossae (Figure 5-4, Region A) comprises a portion of the low thermal inertia area, which also includes Tharsis, Olympus, and Amazonis. Elevated Cl concentrations in this area may be due to the presence of thick, Cl-rich dust at the surface. However, a large portion of this low thermal inertia region (in particular north of 15º latitude to the east of Olympus) does not show significantly high Cl concentrations. Similarly, low thermal inertia regions around Arabia and Elysium do not show distinctively high Cl concentrations or strong spatial linkages with the Cl map. As noted above, analysis with linear multivariate regression models reveal that the parameters of thermal inertia, rock abundance, and albedo show weaker correlations with Cl than do the elemental parameters of H and Si concentration. GRS is sensitive to greater depths than albedo and thermal measurements probe. However it remains unclear if the spatial discrepancies described above are due to 1) differing depths of homogeneous soil and dust components, or 2) compositional differences in these materials at depth. If true, an implication of the former hypothesis would be that Cl-rich soils and dust are thicker in Amazonis than in Arabia.

We have further investigated the hypothesis of aeolian deposition to explain the GRS Cl signature through a simple two-component model involving Cl-rich non-rocky material and Cl-poor rocks. Assuming that the high Cl region west of Tharsis contains thick dust mantles down to the GRS detection depth, we infer a Cl concentration for the non-rock (soil and dust) component based upon the mean concentration obtained from the 2*s* -outlier Region A1 (see Table 5-2 and Figure 5-4b). We investigated whether the two-component model could reproduce the observed range of Cl values using reasonable estimates of rock abundance smoothed to the same resolution as GRS data. Christensen (1986) estimated rock abundances on Mars at 1-x-1° resolution using Viking thermal data and found values typically do not exceed 30-35% aerial coverage. Smoothing of the rock abundance map with the 10°-arc-radius boxcar mean filter previously applied to GRS data results in a maximum smoothed rock abundance of 22% aerial coverage. It is important to point out that Christensen (1986) modeled rock abundance using thermal properties for 10-cm rocks and notes that use of significantly smaller rocks (down to roughly 1-mm) could lead to higher rock abundance estimates within a factor of 2. Thus the actual threshold for maximum smoothed rock abundance may be somewhere between 22-44%.

The model presented here is based on the following parameters for non-rock (NR) and rock (R) components: areal abundance (f_{NR} and f_R), density (ρ_{NR} and ρ_R), bulk density (ρ_T), rock Cl composition measured by landers (Cl_R), non-rock Cl composition determined by GRS (Cl_{NR}), and Cl measured by GRS for a region (Cl_{GRS}). Several relationships exist between these parameters:

(1) $f_{NR} = 1 - f_R$

(2) $\rho_T = f_R \rho_R + f_{NR} \rho_{NR}$

(3) $Cl_{GRS} \rho_T = Cl_R \rho_R f_R + Cl_{NR} \rho_{NR} f_{NR}$

Rewriting these equations, we can estimate the abundance of rock required to dilute the Cl-rich non-rock component to produce a Cl concentration consistent with GRS measurements (Cl_{GRS}) and lander data:

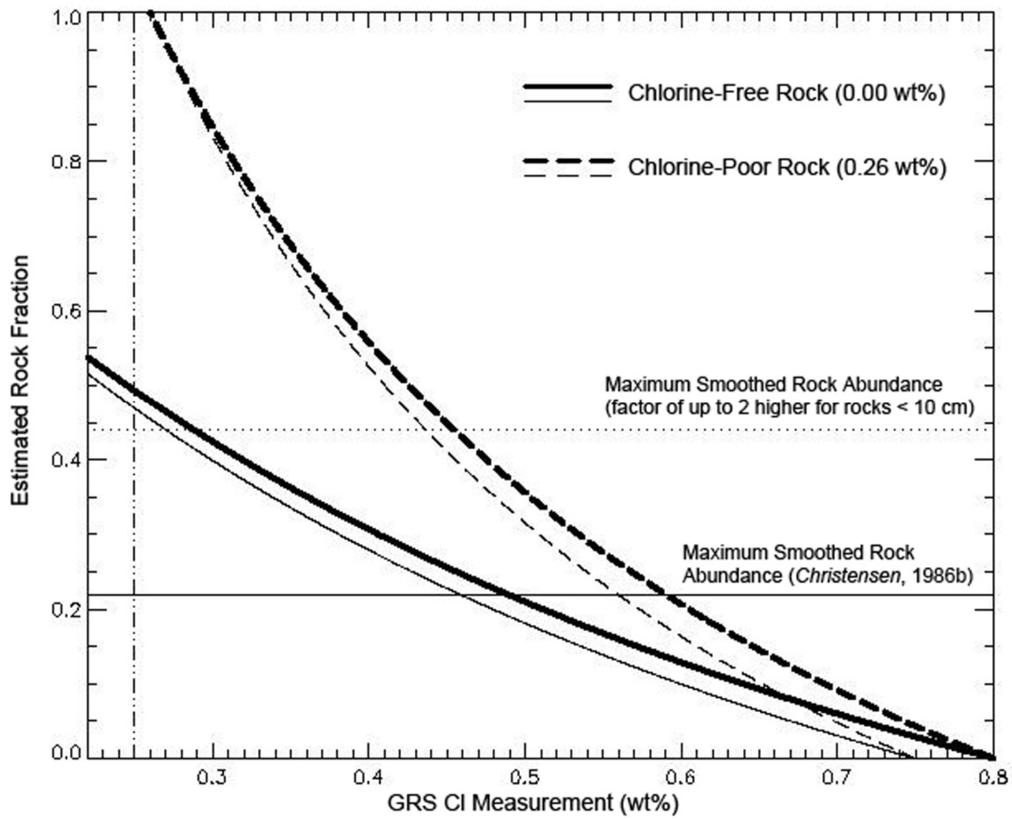
(4) $$f_R = \frac{\rho_{NR}\left(Cl_{NR} - Cl_{GRS}\right)}{\rho_R\left(Cl_{GRS} - Cl_R\right) + \rho_{NR}\left(Cl_{NR} - Cl_{GRS}\right)}$$

Using lander measurements to assign representative values to the non-GRS parameters in Equation 4, we calculate the aerial rock fraction of Cl-poor and Cl-free rocks required to dilute Cl-rich fine material to regional values measured by GRS. The results of this calculation for four sets of parameters are shown in Figure 5-7. In all models, densities of 2.6 and 1.15 g/cm3 were used for rock and fines, respectively (Christensen and Moore, 1992). For the fine component, concentration values of 0.81

and 0.74 wt% Cl were used, which correspond to the mean Cl concentration for Region A1 and the value $1s_m$ below this value (see Table 5-2). Note that these concentration values plot on the x-axis ("GRS Cl Measurement") at a rock abundance of 0% (corresponding to 100% fine material). We then varied the composition of the rock component using values of 0.0 and 0.26 wt% Cl (solid curves shown for Cl-free rock and dotted curves shown for a typical basaltic rock like Humphrey Rock measured at Gusev Crater) (Gellert et al., 2006). The x-axis ranges from the mean value of low Cl Region B1 (0.22 wt% Cl) to the mean value of Cl Region A1 (0.81 wt% Cl). Also plotted are horizontal threshold lines at the maximum smoothed rock abundance estimates by Christensen (1986) described above and a vertical threshold line at 0.27 wt%, a value $1s_m$ above the mean for Region B1 (see Table 5-2).

Using rocks with no Cl (similar to martian meteorites) requires rock abundances of 50~55% aerial coverage to account for the range of Cl concentrations measured by GRS. These results are marginally consistent with the maximum smoothed rock abundance estimates if the average rock sizes are substantially smaller than 10 cm (up to 44% aerial coverage) but are significantly high compared to the estimate based upon 10-cm rocks (22% aerial coverage) (Christensen, 1986). Unreasonably high rock abundances are required to explain the GRS Cl measurement through dilution using rocks with Cl values similar to surface basalts measured by Pathfinder and MER (dashed curves).

Figure 5-7 Two-component Cl mixing model



Representative curves for a two component Cl mixing model. See text for further details. Shown are the estimated areal fractions of Cl-free and Cl-poor rock required to dilute regional Cl concentrations to values observed by GRS, assuming Cl-rich fine material of uniform composition. Density of 2.6 and 1.15 g/cm^3 were used for rocks and fines [Christensen and Moore, 1992]. The modeled Cl compositions used for the non-rock component (0.81 and 0.74 wt% Cl) are shown on the graph where the curves matches a rock fraction of 0% (100% non-rock). These values represent the mean Cl concentration measured in the high Cl Region A1 shown in Figure 4b and a value 1sm below this mean. Vertical threshold is shown at 0.27 wt% Cl, a value 1sm above the mean for low Cl Region B1 in Figure 4b. Horizontal threshold lines are shown at the maximum smoothed rock abundance estimates from Christensen [1986b]. This rock abundance model is based upon thermal properties of 10 cm rocks, and estimates could be a factor of 2 higher if rocks are significantly smaller down to ~1 mm in size (dotted horizontal line).

The model highlights that mixing of homogeneous fines with Cl-free and Cl-poor rocks is an important factor in explaining the GRS Cl result. Given uncertainties in the rock abundance model, we cannot conclusively reject the possibility that regions of very low Cl could be due to very fine-grained Cl-free rock fragments (analogous to crushed martian meteorites) mixed with low density globally homogeneous fine material. Rock abundances may also be higher below the thermal skin depth of a few to ten centimeters upon which the rock abundance model is based (Christensen, 1986; Newsom et al., 2007). However, the tight constraints required to fit the model to both GRS and rock abundance data does not make a strong case that the proposed global fine component is mixed to a uniform Cl concentration across the entire planet. While concentrations for other major elements may be more homogeneous, the Cl concentration value in soils across the globe appears to vary. This result is consistent both with local variations in Cl concentration seen at each of the lander sites (Clark et al., 1982; Gellert et al., 2004; Rieder et al., 2004; Yen et al., 2005) and variations in Cl composition measured by GRS in proposed regions of thickly mantled airborne materials (Newsom et al., 2007). While Cl is enriched in martian soils relative to basaltic rocks, localized mixing and other geologic processes appear to be important factors leading to regional variations in the Cl content of both rocks and fine material. Aeolian deposition of Cl-rich materials likely plays an important role in the distribution of Cl measured by GRS, but it is not clear that this is the only mechanism involved.

5.6.2 Hypothesis 2: Acid-fog Reactions from Volcanic Exhalations

A second geologic mechanism that may have affected the distribution of Cl measured by GRS involves enrichment through volcanic activity. In particular, we propose that the region of high Cl (Figure 5-4, Region A) centered over the Medusae Fossae Formation (MFF) to the west of Tharsis may have been affected by volcanic exhalations that have enriched the amount of Cl in relatively thick deposits interpreted to be ash-flow tuffs and ignimbrites (e.g., Malin, 1979; Scott and Tanaka, 1982; Scott and Chapman, 1991) among other interpretations (Zimbelman et al., 1997).

Tharsis represents the longest-lived site of volcanism on the planet, pulsating for possibly more than 3.5Ga (Anderson et al., 2001; Dohm et al., 2001b, 2006; Baker et al., 2002). Substantial evidence for explosive volcanism (Wilson and Head, 1994) has been identified in the region (e.g., Edgett et al., 1995; Head and Wilson, 1998; Head and Wilson, 1998; Wilson et al., 1998), including 1) burial by fine ash to explain inactivation of transverse dune fields west of Tharsis (Edgett, 1997), 2) thick fine-grained deposits around Arsia Mons (Mouginis-Mark, 2002), and 3) pit craters similar to terrestrial maar craters around Arsia and Pavonis Montes (Scott et al., 1998; Mouginis-Mark, 2002; Wyrick et al., 2004). Hynek et al. (2003) proposed that friable layered deposits found both east and west of Tharsis rise may be volcanic materials deposited by explosive volcanism around Tharsis. It is possible that the Cl-rich region to the west of Tharsis and centered over the MFF is directly related to volcanic activity in the region (Scott and Tanaka, 1986). While other volcanic provinces exist on Mars, it is not clear why these do not show similarly high Cl values. This observation may relate to the timing, composition, or aerial extent of volcanic activity and subsequent resurfacing within the upper few tens of centimeters in these regions.

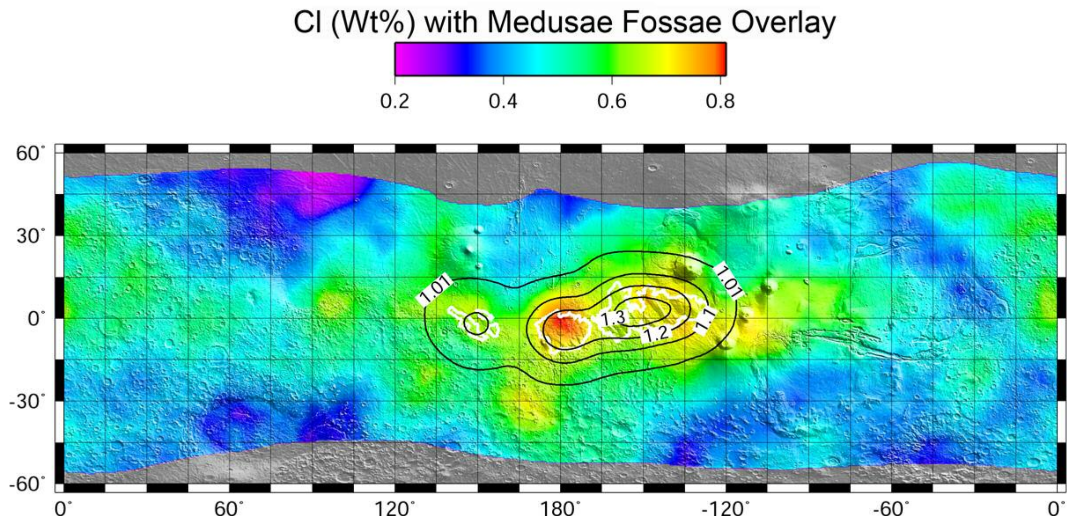
The MFF materials show wind-etched surface morphologies reminiscent of terrestrial ignimbrites and indicative of periods of past and/or current exhumation (Malin, 1979; Scott and Tanaka, 1982; Scott and Tanaka, 1986; e.g., Greeley and Guest, 1987; Scott and Chapman, 1991; Wilson et al., 1998). These relatively thick deposits blanket topographic features across an extended geographic region along the equator west of Tharsis. While the source of these deposits has not been positively identified, volcanism from buried or eroded vents within the MFF or explosive volcanism around the Tharsis rise has been proposed. Evidence also exists for magma-water/water-ice interactions, including structurally-controlled releases of liquid water and other volatiles that dissect the MFF materials (Dohm et al., 2004a). Both the Northwestern Slope Valleys (NSV) region (Dohm et al., 2001a, 2001b, 2004a) and the region to the south of Elysium along the highland/lowland boundary may contain outcrops of MFF materials and have experienced extensive modification through fluvial and other activity (Scott and Chapman, 1995).

The importance of volcanic exhalations of volatiles on the martian regolith has been widely discussed (Clark and Baird, 1979; Settle, 1979; Burns and Fisher, 1990; e.g., Banin et al., 1997; Morris et al., 2000; Tosca et al., 2004). Acid-fog reactions, involving outgassed HCl that dissolves in water to enhance the acidity and Cl content of fog and precipitation associated with volcanic activity, have been proposed as an important solid-aerosol and/or solid-fluid interaction on Mars (Settle, 1979; Banin et al., 1997; Tosca et al., 2004). Cl from acid-fog can be added to the substrate rock in the form of easily solubilized chloride salts. Acid-fog reactions, which typically involve low water/rock ratios under current martian conditions, can effectively deposit Cl through the formation of thin films. Hort and Weitz (2001) also proposed that water released through volcanism is likely to form ice in the cold martian atmosphere. Resulting snowfall could be both acidic and susceptible to melting through heating by hot tephra and regional volcanics, resulting in temporarily higher water/rock ratios.

We propose that ignimbrite deposits associated with MFF materials may have been enriched in Cl through interactions with acid-fog and/or acidic precipitation (likely ice) either during or subsequent to the emplacement of these materials. Low radar reflectivity (Butler, 1995; Edgett et al., 1997), low thermal inertia (Christensen and Moore, 1992), and various morphological features (Tanaka et al., 1992) indicate a finely grained substrate rock in the Medusae Fossae region that may have been well suited for absorbing and holding Cl. Equatorial prevailing winds, which flow from east to west independent of obliquity (Haberle, personal communication, 2005; Haberle et al., 1993), may explain the asymmetry of the Cl-rich region centered to the west of Tharsis. At Gusev Crater which borders with MFF materials, acid-fog reactions have been suggested as a possible mechanism for Cl enrichments found in soils and rock coatings (Arvidson et al., 2004; Haskin et al., 2005; Yen et al., 2005), although aqueous processes described below appear to also be required (Rao et al., 2005). Cl enrichment from volcanic exhalation and increased water abundances for leaching may have occurred contemporaneously during periods of increased volcanism and volcanic exhalation of both water and Cl. While either contemporaneous or subsequent events of aqueous alteration appear to have occurred at Gusev, deposition of Cl in the greater MFF region through volcanic exhalation is consistent with observations at the Gusev plains.

To test the hypothesis that MFF materials may be responsible for the elevated Cl signature, we have modeled the Cl signal that GRS would detect if MFF materials contain elevated Cl content compared to the rest of Mars. Based upon mapping by Scott and Tanaka (1986), Figure 5-8 shows the location of MFF material as white contours overlain on the 5-x-5° smoothed Cl map. This contoured region of Medusae Fossae was assigned a Cl value 1.66 times higher than the Cl value for Pathfinder soil with 3% water-equivalent hydrogen (the soil composition used in our forward calculation model). We then duplicated the same data processing steps that have been applied to the GRS data (Boynton et al., 2007). Figure 5-8 shows the results of this model overlain as black contours. The outer line represents the detection limit of Cl from the Medusae Fossae Formation region. The three inner lines represent values that are 10%, 20%, and 30% higher than the Cl signature expected for our nominal Pathfinder soil. This analysis provides perspective on the effects of the large GRS footprint and data smoothing on GRS data. The match between the predicted GRS detection of a Cl-rich Medusae Fossae region and the actual observations is striking.

Figure 5-8 Chlorine map highlighting Medusae Fossae region



Map showing spatial relationship between Medusae Fossae Formation (MFF) and region of high Cl. Map has been shifted with 180E longitude at the center. White contours show location of MFF materials mapped by [Scott and Tanaka, 1986]. Black contour lines provide data from model showing GRS signal obtained if Medusae Fossae region shown in white is assigned chlorine value 1.66 times that of rest of Mars. Black contours represent where GRS signal would be equal to, 10%, 20%, and 30% higher than global average value for Cl on planet. This model includes all data processing steps applied to the GRS Cl dataset, including smoothing with 10°-arc-radius boxcar mean filter, and shows the effects of the large GRS footprint, atmospheric attenuation, and data smoothing. While still centered over Medusae Fossae, the boundaries of the high Cl region are blurred in the GRS dataset. The spatial overlap between mapped MFF materials, the modeled Cl signal from MFF, and Cl concentration measured by GRS is striking.

It is difficult to constrain the timing of Cl enrichment around Medusae Fossae due to the fact that we may be seeing a signature related to relatively recent volcanism or Cl-rich layers formed earlier in Mars history that have subsequently been exhumed and exposed. As mentioned above, surface morphologies described by Scott and Tanaka (1982) suggest denudation of ignimbrites by wind, which may have exposed fresh surfaces rich in Cl. The heterogeneous distribution of Cl may provide insights into the extent of transport of materials locally enriched in Cl. If Cl-rich surface deposits are being eroded away from the MFF region, the released Cl appears to have not traveled a great distance from its parent source.

5.6.3 Hypothesis 3: Aqueous Processes and Evaporite Deposition

A third possible mechanism for Cl enrichment involves aqueous transport and deposition of Cl through processes involving ground and surface water. Under both current and proposed past martian climatic conditions, chlorides are easily dissolved by liquid water at the surface. Aqueous transport, both horizontally and vertically, could result in depletions and enrichments in Cl across the surface of Mars locally and regionally. It is important to note that, due to their high solubilities, Cl and Br precipitate from aqueous solutions only after concentrations become very high (Rao et al., 2005), which is most likely after significant evaporation leaving spatially isolated pools. Evaporation can also occur when small sections of regional water bodies have become isolated. In both cases, the deposited precipitate sequence depends more upon local conditions within each isolated pool than on regional geochemistry. This effect is seen in the variability of Cl measured at Meridiani (Rieder et al., 2004). Regional evaporitic conditions, especially for outcrop-forming processes, may be tracked more effectively using less soluble ions such as sulfates, which precipitate earlier when the water body is more regional than local. We are currently pursuing reliable concentration estimates for the elements S and U, which have lower S/N in the gamma ray spectrum. Additional global GRS data for these mobile elements may be important for identifying definitive geochemical evidence for aqueous surface processes at large regional scales (Taylor et al., 2007).

At the Meridiani landing site, MER results provide strong evidence for formation of salt bearing sedimentary rocks under conditions involving episodic liquid water and probable evaporitic conditions (Kargel, 2004; Rieder et al., 2004; Clark et al., 2005; McLennan et al., 2005). Region E shown in Figure 5-4a is moderately enriched in Cl and the extends to the north of the landing site. While the previously discussed influences of Cl-rich aeolian dust deposits around Arabia (Christensen, 1986) or potential volcanic airfall deposits (Hynek et al., 2003) cannot be ruled out, the possibility exists that evaporite deposits spread throughout the region on scales much larger than the Opportunity sample field may contribute to the elevated Cl signal seen by GRS. This possibility is also consistent with the primordial impact basin model by Dohm et al. (2004b), which proposed that Arabia Terra is the site of an ancient, gigantic impact basin that accumulated thick sedimentary deposits of ancient crustal materials from regions surrounding the basin (Malin and Edgett, 2000; Malin and Edgett, 2001). Later uplift, possibly related to the roughly antipodal growth of Tharsis, could have resulted in differential erosion exposing these older sedimentary sequences enriched in Cl and H deposits around Arabia Terra (Boynton et al., 2007).

For the elevated Cl signature recorded in the MFF region (Figure 5-4, Region A), aqueous processes must also be considered along with other processes. While the region west of Tharsis does not currently involve substantial topographic lows, geologic mapping indicates evidence for long-lived aqueous activity and fluvial processes in the MFF region along the highland-lowland boundary (Scott and Tanaka, 1986; e.g., Chapman and Tanaka, 1993; Parker et al., 1993; Craddock and Greeley, 1994; Zimbelman et al., 1994; Scott and Chapman, 1995; Dohm et al., 2001a, 2001b). Channels dissect both Amazonis and MFF materials (Scott and Zimbelman, 1995), and late Hesperian/Amazonian sapping channels are found in the Mangala Valles and NSV region (Dohm et al., 2004a). Based upon evidence found in soils and rock coatings, the plains of nearby Gusev Crater have also been altered by the presence of small amounts of liquid water (Arvidson et al., 2004; Haskin et al., 2005; Rao et al., 2005; Yen et al., 2005). Rao et al. (2005) emphasized that, to explain elemental correlations with Cl, S, and Br found in rock coatings, more liquid water is required than can be provided through thin film deposition alone under current climatic conditions. Many causes have been proposed for episodes of increased water column abundances, including periods of higher obliquity (Jakosky and Carr, 1985; Richardson and Wilson, 2002; e.g., Forget et al., 2006), impacts, catastrophic outflows, and increased volcanism (Hort and Weitz, 2001). Based upon these observations and hypotheses, it is likely that aqueous processes have modified the distribution of Cl found in the MFF region.

Leaching may have been important for depleting concentration values in low Cl regions. The southern highlands region is an ancient surface that appears to be depleted in both Fe and Cl (Boynton et al., 2007). It is unclear whether these elements 1) were originally depleted in the native rocks of the region, or 2) have been eroded from the near-surface of this region through aeolian and/or aqueous processes. In the latter case, leaching of these materials either from the southern highlands towards the northern lowlands and from the near-surface into the subsurface are both possibilities.

The low Cl region to the north of Syrtis Major (Region B) does not show a corresponding Fe depletion. Interestingly, this region extends towards the southern edge of the Vastitas Borealis region, the site of a proposed ancient ocean (Parker et al., 1993; Fairén et al., 2003). If present, substantial deposits of Cl do not appear to be exposed within the upper few tens of centimeters. While one might expect to find localized evaporite deposits enriched in Cl, we again emphasize that a more likely regional signature at larger scales might be expected for the element S. Future work regarding the distribution of S may prove instructive.

5.6.4 Hypothesis 4: Chemical Alteration through Hydrothermal Activity

A final mechanism considered here involves alteration and mobilization in hydrothermal processes. Two primary types of hydrothermal fluid systems are found on Earth: 1) neutral-chloride type involving abundant water supply, high Cl concentrations, and low S/Cl ratios; 2) acid-sulfate type involving limited water and high S/Cl ratios (Newsom et al., 1999). On Mars, hydrothermal activity could result from interactions of water with heated airfall deposits, impact events, or localized volcanism. Low water/rock ratios on the planet would seem to favor formation and preservation of acid-sulfate type systems.

Currently, the GRS dataset neither confirms nor denies the presence of hydrothermal activity. The positive association of Cl with H is consistent with models involving both types of hydrothermal systems because by definition water would be involved. However, this correlation is not conclusive as H could also be enriched through non-hydrothermal processes, including climatic effects coupled with a matrix favorable for retaining water. A reliable measurement of the element S might provide stronger constraints. Low S in regions of high Cl may indicate neutral-chloride type hydrothermal activity. Alternatively, low water/rock hydrothermal conditions may result in regions high in S relative to Cl. Further remote sensing and in situ measurements are required to substantiate and quantify the importance of hydrothermal activity at the martian surface, and GRS may yet provide insightful geochemical context through measurement of the element S.

5.7 Summary

In agreement with lander measurements and meteorite isotope work (Rao et al., 2002), Cl is significantly enriched at the surface relative to the martian meteorites and estimates for the bulk composition of the planet. Cl is heterogeneously distributed over the surface and varies by over a factor of ~4 even after smoothing with a 10º-arc-radius filter. Several contiguous, geographically large regions of high and low Cl concentrations are present. In particular, a region centered over the Medusae Fossae Formation (MFF) west of Tharsis shows significantly elevated Cl. Distinctly low Cl values are observed in the southern highlands and in a region north of Syrtis Major extending into Utopia Planitia. Moderate but measurable differences from the global mean are found around the outflow channels of Chryse and Acidalia Planitia and around Arabia Terra. Some transitional concentration values may be artificial due to effects of smoothing between regions of high and low Cl. Based upon hierarchical multivariate correlations, Cl is positively linked with H and negatively associated with Si and thermal inertia. Together, these parameters account for as much as 40% of the global variability in Cl and show significantly stronger correlations than other elemental and physical parameters.

A strong spatial overlap between the Cl-rich region west of Tharsis and the previously mapped MFF points towards Cl-enriched materials in this region. We propose that denudation of volcanic ignimbrite deposits enriched in Cl through reactions with acid-fog or acidic precipitation (at some point in the formation's history) plus some other aqueous activity as suggested for Gusev Crater (Arvidson et al., 2004; Haskin et al., 2005; Rao et al., 2005) may be responsible for the high concentrations reported here. Transport of Cl in liquid ground or surface water may have depleted Cl in some regions (possibly ancient southern highlands) through leaching and erosion and enhanced Cl in other regions (Arabia Terra and MFF) through deposition and evaporitic processes (e.g., Kargel, 2004). However, because Cl variations in aqueous environments are highly sensitive to local conditions, sulfates may provide a better indicator of regional aqueous processes. While more difficult due to lower S/N, future determination of concentration values for elements such as S and U may provide additional insight. Weak correlations with parameters related to surface dust (thermal inertia, albedo, and rock abundance) lend support to the idea that the distribution is also influenced by Cl-rich fine deposits transported by aeolian processes. However, these correlations do not appear to account for all of the observed variability, as a simplified two-component model highlights difficulties with attempting to invoke aeolian processes as the only relevant mechanism. Aeolian, volcanic, aqueous, and hydrothermal processes may have played varying roles over different regions and times in the complex history of the martian surface. The most significant implication of the non-uniform distribution of Cl at regional to global scales is that Mars is complicated and requires further study to explain the interesting compositional diversity expressed at the near surface.

APPENDIX A: STUDENT-SUPPLIED RESPONSE SURVEY, VERSION A

Students provided written responses to the following open-ended prompt during the Fall 2003 and Spring 2004 semesters. Coding of student responses is summarized in Chapter 2.

Greenhouse Effect Questionnaire

You've heard about the Greenhouse Effect before, but what is it really? Describe in as much detail as possible what you think the Greenhouse Effect is and the science behind how it occurs. Please provide a sketch if possible.

SSR.vA Fall 2003/Spring 2004

APPENDIX B: CODING SCHEMAS FOR SSR.VA SURVEY

This appendix provides the initial and final coding schemas that were used to code SSR.vA surveys as described in Section 2.2.1.

Initial Coding Schema

Survey #: __________ F03P06 F03P07 S04P09 S04S02 S04M52

Gases
- ❑ GASES
- ❑ GHG
- ❑ H2O
- ❑ CO2
- ❑ CH4
- ❑ CO
- ❑ CFC
- ❑ SO2
- ❑ O3

Sources
- ❑ ARTIFICIAL
- ❑ HUMANS
- ❑ POP
- ❑ TECH/IND
- ❑ CARS
- ❑ FOSSIL
- ❑ GASOLINE
- ❑ POLL
- ❑ AEROSOL
- ❑ REFRIDGE
- ❑ CHEMICALS
- ❑ ACID RAIN
- ❑ DEFOREST
- ❑ RADIATION

- ❑ NATURAL
- ❑ PLANTS
- ❑ PHOTO
- ❑ ANIMALS
- ❑ HUMIDITY
- ❑ VOLCANOS

Harmful/Beneficial
- ❑ HARMFUL
- ❑ NEUTRAL
- ❑ BENEFICIAL

Consequences
- ❑ ATMOSPHERE
- ❑ TEMP_INC
- ❑ WEATHER
- ❑ HUMIDITY
- ❑ CLIMATE
- ❑ OZONE
- ❑ AIR-POLL
- ❑ THICKER

- ❑ OCEAN
- ❑ ICE-MELT
- ❑ SEA-LEVEL
- ❑ TEMP
- ❑ FLOODING

- ❑ NATURE
- ❑ NEC-LIFE
- ❑ BIODIVER
- ❑ ANIM-DEC
- ❑ PLANT-INC
- ❑ HURT_ENV
- ❑ SURF_DRIES

- ❑ HUMANS
- ❑ SICKNESS
- ❑ CANCER

GHE/GW/O3
- ❑ GHE=GW
- ❑ 03=GW
- ❑ GHE=O3_DEP
- ❑ GHE->03
- ❑ O3->GW
- ❑ 03->GHE
- ❑ GHE->GW
- ❑ GW->GHE
- ❑ GW->O3

Student Models
- ❑ OZONE
- ❑ O3-HOLE
- ❑ O3-DEP
- ❑ UV-INC
- ❑ OZONE_TRAPS

- ❑ EQUIL/BAL
- ❑ IR
- ❑ WAVE-DEP
- ❑ CONVECTION
- ❑ WATER_CYCLE

Light Interactions
- ❑ ABSORB
- ❑ RE-EMIT
- ❑ REFLECT
- ❑ MAGNIFY
- ❑ TRAP
- ❑ INSULATE

Analogies
- ❑ BLANKET
- ❑ OVEN
- ❑ GH
- ❑ GH-RAD
- ❑ GH-CIRC

Energy Flow
- ❑ I-ENERGY
- ❑ I-SUN
- ❑ I-RAD/LITE
- ❑ I-HEAT
- ❑ I-LONG
- ❑ I-SHORT
- ❑ I-GAS
- ❑ I-RADIO
- ❑ I-IR
- ❑ I-UV

- ❑ O-ENERGY
- ❑ O-SUN
- ❑ O-RAD/LITE
- ❑ O-HEAT
- ❑ O-LONG
- ❑ O-SHORT
- ❑ O-GAS
- ❑ O-RADIO
- ❑ O-IR
- ❑ O-UV

- ❑ T-ENERGY
- ❑ T-SUN
- ❑ T-RAD/LITE
- ❑ T-HEAT
- ❑ T-LONG
- ❑ T-SHORT
- ❑ T-GAS
- ❑ T-MOISTURE
- ❑ T-RADIO
- ❑ T-IR
- ❑ T-UV

Form F03P07

Final Coding Schema

Survey #: ________ F03P06 F03P07 <u>S04P09</u> S04S02 S04M52

Gases
- GASSES
- GHG
- H2O
- CO2
- CH4
- CO
- CFC
- SO2
- O3
- O2
- C
- NO2
- N
- FREON
- NH4
- NO
- N
- H

Sources
- ARTIFICIAL
- HUMANS
- POP
- TECH/IND
- CARS
- FOSSIL
- GASOLINE
- POLL
- AEROSOL
- REFRIDGE
- CHEMICALS
- ACID RAIN
- DEFORESTATION
- RADIATION
- CLOUDS
- MIRRORS
- THIN_ATM
- LIGHT_POLL

- NATURAL
- PLANTS
- PHOTO
- ANIMALS
- HUMIDITY
- VOLCANOS
- ORBIT
- LA NINA

Harmful/ Beneficial
- HARMFUL
- NEUTRAL
- BENEFICIAL

Consequences
- ATMOSPHERE
- TEMP_INC
- TEMP_STAB
- TEMP_DEC
- WEATHER
- HUMIDITY
- CLIMATE
- OZONE
- AIR-POLL
- THICKER
- THINNER
- CO-REMOVE
- O2-DECREASE

- OCEAN
- ICE-MELT
- SEA-LEVEL
- TEMP
- FLOODING
- ACID RAIN

- NATURE
- NEC-LIFE
- BIODIVER
- ANIM-DEC
- PLANTS-INC
- PLANTS-DEC
- HURT_ENV
- SURF_DRIES
- CORRAL_BLEACH
- THINGS_BURN

- HUMANS
- SICKNESS
- CANCER

GHE/GW/O3
- GHE=GW
- O3=GW
- GHE=O3_DEP
- GHE->O3
- O3->GW
- O3->GHE
- GHE->GW
- GW->GHE
- GW->O3

Student Models
- OZONE_LAYER
- O3-HOLE
- O3-DEP
- O3-INC
- UV-INC
- OZONE_TRAPS

- EQUIL/BALANCE
- IR
- WAVE-DEP
- CONVECTION
- CIRCULATION
- WATER_CYCLE
- CARBON CYCLE
- SOLAR POWER
- SURF_INC

Light Interactions
- ABSORB
- RE-EMIT
- REFLECT/BOU
- MAGNIFY
- TRAP
- INSULATE
- REFRACT
- CONDENSE_LITE
- ATTRACT_LITE

Analogies
- BLANKET
- OVEN
- LENSE
- FILTER
- SHIELD
- MICROWAVE
- BUBBLE
- TELESCOPE
- DOME
- WALL
- CONDUCTOR
- GH
- GH-RAD
- GH-CIRC

Energy Flow
- I-ENERGY
- I-SUN
- I-RAD/LITE
- I-HEAT
- I-LONG
- I-SHORT
- I-GAS
- I-RADIO
- I-IR
- I-VIS
- I-UV
- I-XRAY
- I-GAMMA

- O-ENERGY
- O-SUN
- O-RAD/LITE
- O-HEAT
- O-LONG
- O-SHORT
- O-GAS
- O-RADIO
- O-IR
- O-VIS
- O-UV
- O-XRAY
- O-GAMMA

- T-ENERGY
- T-SUN
- T-RAD/LITE
- T-HEAT
- T-LONG
- T-SHORT
- T-GAS
- T-MOISTURE
- T-RADIO
- T-IR
- T-VIS
- T-UV
- T-XRAY
- T-GAMMA

S04P09

APPENDIX C: STUDENT-SUPPLIED RESPONSE SURVEY, VERSION B

This appendix provides a copy of a second student supplied response survey that was developed and administered during Spring 2004. This survey is described in further detail in Sections 2.2.2 and 2.11.

Name: ____

Preliminary Survey

You've heard about "Ozone Depletion," the "Greenhouse Effect," and "Global Warming," but what are these really? Describe in as much detail as possible your conception of what each of these atmospheric phenomena is. How are they related or not related to each other? Please provide sketches if possible.

APPENDIX D: STUDENT SUPPLIED RESPONSE SURVEY, VERSION C

This appendix provides the four versions of Survey SSR.vC. These surveys were administered during Spring 2005 along with the six versions of GECI.vA (see Appendix E). As described in Sections 2.2.2 and 3.1.1, roughly equal numbers of the ten surveys were passed out to each class, with students completing one survey each. All student were asked to answer Items 22-24, provided at the end of this appendix.

Results from SSR.vC1 on the primary greenhouse gases are provided in Section 2.8. Results from SSR.vC2 on pollution are provided in Sections 2.5 and 2.9. Results from SSR.vC3 on greenhouse effect analogies are provided in Section 2.7. Results from SSR.vC4 on energy flow are provided in Section 2.4.4.

GECI.vC1

1) List the primary greenhouse gases in Earth's atmosphere.

Describe the main characteristic of these gases that make them greenhouse gases.

When you look towards the sky, which of the above substances, if any, could you see with your naked eye? Justify your response.

GECI.vC2

2) A common quote used by students who were asked to explain the greenhouse effect is that "Pollution is a major cause of the greenhouse effect." What form or forms of pollution do you think these students are referring to and how does the pollution cause the greenhouse effect, if at all?

GECI.vC3

3) Pick one of the following and describe why it is a good analogy for characterizing the behavior of greenhouse gases in the atmosphere. Also, describe any weaknesses with the analogy.

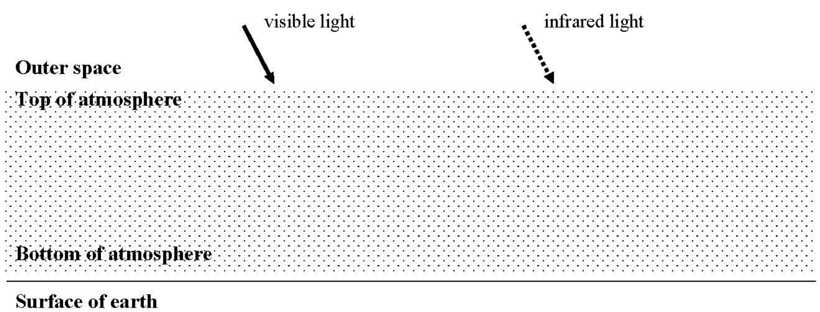
a) a blanket
b) a shield
c) a wall
d) an oven
e) a lense
f) a bubble
g) a filter
h) a dome
i) a microwave
j) a funnel
k) a sponge
l) a conductor

Strengths as an analogy:

Weaknesses as an analogy:

GECI.vC4

4) The diagram below shows visible light (solid arrow) and infrared light (dashed arrow) from the Sun arriving at the top of Earth's atmosphere. Show what happens to each of these forms of light as they interact with the atmosphere and surface. Use SOLID arrows to represent visible light and DASHED arrows to represent infrared light. Provide a brief description of what is going on in your drawing. If other forms of light are involved, describe how you show this in the diagram.



Description of what your diagram shows:

22) Would you be willing to participate in a short interview to discuss your responses to this survey? NOTE: Indicating "yes" to this does not guarantee you will be selected to be interviewed, and if selected, you will still have the opportunity to refuse the interview.
    a) Yes
    b) No

23) What is your gender?
    a) Male
    b) Female

24) Have you ever had a class that covered the topic of the greenhouse effect?
    a) Yes
    b) No

APPENDIX E: GREENHOUSE EFFECT CONCEPT INVENTORY, VERSION A

This appendix provides the items that comprised the six versions of Survey GECI.vA. Items 1-10 were asked on Survey GECI.vA1, and Items 11-21 were asked on GECI.vA2. Subsets of these items were asked along with an open-ended prompt directing students to explain their reasoning on Survey GECI.vA1A (Items 1-5), GECI.vA1B (Items 6-10), GECI.vA2A (Items 11-15), GECI.vA2B (Items 16-21). All student were asked to answer Items 22-24, provided at the end of this appendix. See Section 3.1.1 for more details.

These surveys were administered during Spring 2005 along with four versions of SSR.vC (see Appendix D). As described in Sections 2.2.2 and 3.1.1, roughly equal numbers of the ten surveys were passed out to each class, with students completing one survey each.

Results from GECI.vA survey items are discussed throughout Chapter 3 and listed in Appendix F.

GECI.vA1 (Items 1-10)

1) Which of the following is a greenhouse gas? Circle all that apply.
   - ❑ Water (H_2O)
   - ❑ Carbon dioxide (CO_2)
   - ❑ Carbon monoxide (CO)
   - ❑ Oxygen (O_2)
   - ❑ Nitrogen (N_2)
   - ❑ Ozone (O_3)
   - ❑ Methane (CH_4)
   - ❑ Ammonia (NH_4)
   - ❑ Sulfur dioxide (SO_2)
   - ❑ Nitrogen oxides (NO_2, N_2O)
   - ❑ Chloroflourocarbons (CFCs)
   - ❑ Smoke particles
   - ❑ Freon
   - ❑ Hydrogen (H_2)
   - ❑ Helium (He)
   - ❑ Smog

2) Which one of the following is most responsible for heating Earth's surface?
   a) Visible light given off by the Sun passing directly through the atmosphere
   b) Visible light given off by the atmosphere towards the surface
   c) Infrared light given off by the atmosphere towards the surface
   d) Ultraviolet light given off by the Sun passing through the ozone hole
   e) Heat given off by cars, factories, and other human activities

3) The greenhouse effect is
   a) a phenomenon that has operated in Earth's atmosphere for most of its history.
   b) a recent phenomenon caused by natural processes.
   c) a recent phenomenon caused by the burning of fossil fuels.
   d) a recent phenomenon caused by destruction of the ozone layer.
   e) none of the above.

4) During the nighttime, Earth's surface gives off mainly which of the following forms of energy? Circle all that apply.
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

5) Greenhouse gases raise Earth's overall surface temperature by
   a) destroying the ozone layer and allowing more sunlight into the atmosphere.
   b) affecting the flow of energy through the atmosphere.
   c) causing an increase in the amount of clouds and rainfall.
   d) trapping heat permanently in the atmosphere.
   e) magnifying and focusing sunlight in the atmosphere.

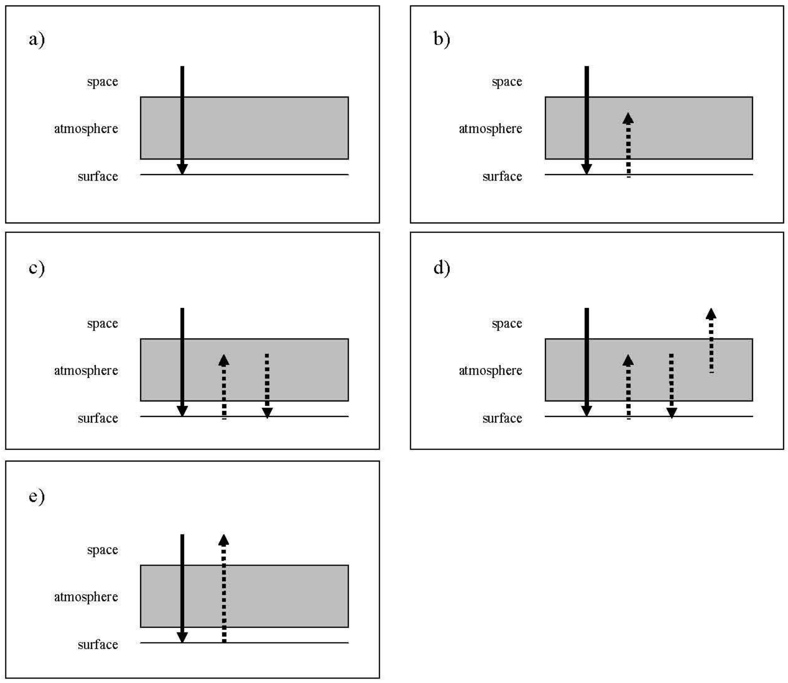
6) Earth's atmosphere is heated mainly by which of the following forms of energy? Circle all that apply.
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

7) Which of the following is true about the greenhouse effect and liquid water on Earth?
   a) The greenhouse effect warms the planet enough for water to be a liquid on Earth.
   b) The greenhouse effect warms the planet, but not enough to affect whether water can be a liquid on Earth.
   c) The greenhouse effect cools the planet enough for water to be a liquid on Earth.
   d) The greenhouse effect cools the planet, but not enough to affect whether water can be a liquid on Earth.
   e) The greenhouse effect does not change the temperature of the planet.

8) The Sun mainly gives off which of the following forms of energy? Circle all that apply.
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

9) Global warming is
   a) a phenomenon that has operated in Earth's atmosphere for most of its history.
   b) a recent phenomenon caused by natural processes.
   c) a recent phenomenon caused by gases released by burning fossil fuels.
   d) a recent phenomenon caused by destruction of the ozone layer.
   e) none of the above.

10) Each diagram below shows Earth's surface, the atmosphere, and outer space. Select the one answer that best describes how visible light (solid arrow) and infrared light (dashed arrows) are absorbed and given off by each of these three components.



22) Would you be willing to participate in a short interview to discuss your responses to this survey? NOTE: Indicating "yes" to this does not guarantee you will be selected to be interviewed, and if selected, you will still have the opportunity to refuse the interview.
  a) Yes
  b) No

23) What is your gender?
  a) Male
  b) Female

24) Have you ever had a class that covered the topic of the greenhouse effect?
  a) Yes
  b) No

GECI.vA2 (Items 11-21)

11) During the daytime, Earth's surface mainly gives off which of the following forms of energy? Circle all that apply.
    a) radio
    b) infrared
    c) visible
    d) ultraviolet
    e) x-ray

12) Earth's overall surface temperature is
    a) warmer than it would be without greenhouse gases.
    b) cooler than it would be without greenhouse gases.
    c) the same temperature as it would be without greenhouse gases.
    d) has not yet been accurately measured.

13) Which of the following describes how visible light from the Sun interacts with Earth's surface? Circle all that apply.
    a) Visible light is reflected by the surface as infrared light.
    b) Visible light is reflected by the surface as visible light.
    c) Visible light is absorbed by the surface which then gives off visible light.
    d) Visible light is absorbed by the surface which then gives off infrared light.
    e) Visible light is absorbed by the surface which then gives off ultraviolet light.

14) If humans civilization had never developed on Earth, would there be a greenhouse effect? Circle all that apply.
    a) Yes, the greenhouse effect has always been present in the atmosphere.
    b) Yes, the greenhouse effect is caused by plants giving off greenhouse gases through photosynthesis.
    c) No, the greenhouse effect is caused by humans breathing out greenhouse gases.
    d) No, the greenhouse effect is caused by humans burning of fossil fuels.
    e) No, the greenhouse effect is caused by humans producing aerosols and refrigerants.

15) Earth's atmosphere mainly gives off which of the following forms of energy? Circle all that apply.
    a) radio
    b) infrared
    c) visible
    d) ultraviolet
    e) x-ray

16) With the greenhouse effect, which of the following most strongly affects Earth's overall surface temperature?
    a) heat released by factories and other industrial activities
    b) ultraviolet light passing through the ozone hole
    c) infrared light that is absorbed and then given off by gases in the atmosphere
    d) air pollution trapped in the atmosphere by greenhouse gases
    e) gas molecules circulating in the atmosphere because hot air rises

17) Earth's surface is heated mainly by which of the following forms of energy? Circle all that apply.
    a) radio
    b) infrared
    c) visible
    d) ultraviolet
    e) x-ray

18) Which of the following describes the cause(s) of global warming? Circle all that apply.
   a) Increase of the greenhouse effect causes global warming.
   b) Decrease of ozone causes global warming.
   c) Increase of the greenhouse effect causes decrease of ozone which causes global warming.
   d) Decrease of ozone causes increase of the greenhouse effect which causes global warming.
   e) None of the above.

19) Which of the following describes how infrared light interacts with greenhouse gases in Earth's atmosphere? Circle all that apply.
   a) Infrared light is reflected by greenhouse gases as infrared light.
   b) Infrared light is reflected by greenhouse gases as visible light.
   c) Infrared light is absorbed by greenhouse gases which then give off visible light.
   d) Infrared light is absorbed by greenhouse gases which then give off infrared light.
   e) Infrared light is absorbed by greenhouse gases which then give off ultraviolet light.

20) Greenhouse gases interact most strongly with which of the following forms of energy? Circle all that apply.
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

21) If greenhouse gases were to permanently trap energy in our atmosphere, the temperature of the atmosphere would
   a) increase forever.
   b) eventually stabilize at a higher temperature.
   c) not change.
   d) eventually stabilize at a lower temperature.
   e) decrease forever.

22) Would you be willing to participate in a short interview to discuss your responses to this survey? NOTE: Indicating "yes" to this does not guarantee you will be selected to be interviewed, and if selected, you will still have the opportunity to refuse the interview.
   a) Yes
   b) No

23) What is your gender?
   a) Male
   b) Female

24) Have you ever had a class that covered the topic of the greenhouse effect?
   a) Yes
   b) No

APPENDIX F: GECI.VA RESPONSE FREQUENCIES

This appendix provides the response frequencies for each of the items on Survey GECI.vA (see Appendix E). Because the six versions of the survey were administered with different subsets of the 21 survey items, responses from survey versions with the same item have been combined. This is the reason why the number of cases varies between Items 1-5, 6-10, 11-15, and 16-21. See Appendix E and Section 3.1.1 for more details on survey administration.

GECI.vA Item Options	Pre-Instruction Survey Count	Total N	Percent	Post-Instruction Survey Count	Total N	Percent
1-CO2	68	98	69.4	61	68	89.7
1-CO	41	98	41.8	9	68	13.2
1-O2	33	98	33.7	29	68	42.6
1-N2	33	98	33.7	24	68	35.3
1-H2O	33	98	33.7	46	68	67.6
1-O3	30	98	30.6	22	68	32.4
1-CH4	29	98	29.6	15	68	22.1
1-NO2	24	98	24.5	11	68	16.2
1-H2	24	98	24.5	10	68	14.7
1-CFC	24	98	24.5	11	68	16.2
1-Smog	22	98	22.4	4	68	5.9
1-SO2	18	98	18.4	13	68	19.1
1-SMOKE	16	98	16.3	3	68	4.4
1-He	16	98	16.3	4	68	5.9
1-FREON	15	98	15.3	5	68	7.4
1-NH4	7	98	7.1	3	68	4.4
2A	49	98	50.0	43	68	63.2
2B	6	98	6.1	4	68	5.9
2C	12	98	12.2	17	68	25.0
2D	25	98	25.5	4	68	5.9
2E	4	98	4.1	1	68	1.5
3A	29	98	29.6	44	68	64.7
3B	5	98	5.1	8	68	11.8
3C	24	98	24.5	8	68	11.8
3D	32	98	32.7	1	68	1.5
3E	6	98	6.1	7	68	10.3
4A	15	98	15.3	6	68	8.8
4B	61	98	62.2	61	68	89.7
4C	18	98	18.4	8	68	11.8
4D	18	98	18.4	5	68	7.4
4E	8	98	8.2	4	68	5.9
5A	38	98	38.8	9	68	13.2
5B	20	98	20.4	30	68	44.1
5C	2	98	2.0	0	68	0.0
5D	34	98	34.7	28	68	41.2
5E	3	98	3.1	3	68	4.4
6A	10	97	10.3	1	68	1.5
6B	34	97	35.1	50	68	73.5
6C	36	97	37.1	49	68	72.1
6D	70	97	72.2	20	68	29.4
6E	9	97	9.3	1	68	1.5

GECI.vA Item Option	Pre-Instruction Survey Count	Total N	Percent	Post-Instruction Survey Count	Total N	Percent
7A	41	97	42.3	50	68	73.5
7B	34	97	35.1	14	68	20.6
7C	7	97	7.2	0	68	0.0
7D	5	97	5.2	1	68	1.5
7E	6	97	6.2	1	68	1.5
8A	10	97	10.3	9	68	13.2
8B	34	97	35.1	28	68	41.2
8C	42	97	43.3	53	68	77.9
8D	78	97	80.4	49	68	72.1
8E	21	97	21.6	13	68	19.1
9A	13	97	13.4	22	68	32.4
9B	10	97	10.3	11	68	16.2
9C	36	97	37.1	24	68	35.3
9D	41	97	42.3	11	68	16.2
9E	4	97	4.1	1	68	1.5
10A	4	97	4.1	0	68	0.0
10B	17	97	17.5	5	68	7.4
10C	24	97	24.7	13	68	19.1
10D	33	97	34.0	40	68	58.8
10E	14	97	14.4	8	68	11.8
11A	18	103	17.5	3	72	4.2
11B	41	103	39.8	60	72	83.3
11C	29	103	28.2	24	72	33.3
11D	57	103	55.3	9	72	12.5
11E	9	103	8.7	1	72	1.4
12A	54	103	52.4	47	72	65.3
12B	41	103	39.8	25	72	34.7
12C	3	103	2.9	1	72	1.4
12D	5	103	4.9	0	72	0.0
12E	1	103	1.0	0	72	0.0
13A	15	103	14.6	13	72	18.1
13B	38	103	36.9	20	72	27.8
13C	24	103	23.3	15	72	20.8
13D	19	103	18.4	46	72	63.9
13E	27	103	26.2	2	72	2.8
14A	34	103	33.0	53	72	73.6
14B	40	103	38.8	21	72	29.2
14C	3	103	2.9	4	72	5.6
14D	33	103	32.0	10	72	13.9
14E	23	103	22.3	6	72	8.3

GECI.vA Item Option	Pre-Instruction Survey			Post-Instruction Survey		
	Count	Total N	Percent	Count	Total N	Percent
15A	21	103	20.4	5	72	6.9
15B	48	103	46.6	49	72	68.1
15C	32	103	31.1	28	72	38.9
15D	56	103	54.4	12	72	16.7
15E	11	103	10.7	1	72	1.4
16A	4	97	4.1	4	73	5.5
16B	35	97	36.1	8	73	11.0
16C	23	97	23.7	43	73	58.9
16D	33	97	34.0	11	73	15.1
16E	6	97	6.2	3	73	4.1
17A	4	97	4.1	0	73	0.0
17B	38	97	39.2	33	73	45.2
17C	22	97	22.7	53	73	72.6
17D	75	97	77.3	22	73	30.1
17E	1	97	1.0	0	73	0.0
18A	46	97	47.4	38	73	52.1
18B	44	97	45.4	26	73	35.6
18C	42	97	43.3	11	73	15.1
18D	29	97	29.9	11	73	15.1
18E	6	97	6.2	11	73	15.1
19A	17	97	17.5	15	73	20.5
19B	11	97	11.3	9	73	12.3
19C	18	97	18.6	8	73	11.0
19D	27	97	27.8	30	73	41.1
19E	29	97	29.9	8	73	11.0
20A	4	97	4.1	2	73	2.7
20B	50	97	51.5	47	73	64.4
20C	24	97	24.7	26	73	35.6
20D	59	97	60.8	23	73	31.5
20E	6	97	6.2	0	73	0.0
21A	52	97	53.6	43	73	58.9
21B	35	97	36.1	22	73	30.1
21C	3	97	3.1	0	73	0.0
21D	1	97	1.0	3	73	4.1
21E	3	97	3.1	2	73	2.7

APPENDIX G: GREENHOUSE EFFECT CONCEPT INVENTORY, VERSION B

This appendix provides copies of the two versions of Survey GECI.vB administered during Fall 2005. Half of the students in each class completed Items 1-19 while the other half completed Items 21-39. See Section 3.1.2 for further details.

Results from GECI.vB survey items are discussed throughout Chapter 3 and listed in Appendix H.

If the <u>DAY of your birth</u> is an <u>ODD NUMBER</u>, please bubble in your answers to <u>Questions 1-19</u> on the scantron sheet provided. Take care to bubble in the right question number on the scantron. If the day of your birth is an even number, please turn to Page 7.

1) The Sun mainly gives off (radiates) which two forms of energy?
    a) ultraviolet and x-ray
    b) ultraviolet and infrared
    c) visible and ultraviolet
    d) infrared and visible
    e) radio and infrared

2) Which of the following are the most abundant greenhouse gases in Earth's atmosphere?
    a) carbon dioxide (CO_2) and methane (CH_4)
    b) ozone (O_3) and carbon dioxide (CO_2)
    c) nitrogen (N_2) and oxygen (O_2)
    d) hydrogen (H_2) and helium (He)
    e) water vapor (H_2O) and carbon dioxide (CO_2)

3) Earth's surface absorbs and is heated by mainly which two forms of energy?
    a) ultraviolet and x-ray
    b) ultraviolet and infrared
    c) visible and ultraviolet
    d) infrared and visible
    e) radio and infrared

4) On average, the total amount of energy leaving the Earth system to space
    a) is greater than the amount of energy arriving from space.
    b) is less than the amount of energy arriving from space.
    c) is equal to the amount of energy arriving from space.
    d) depends upon the concentration of greenhouse gases in the atmosphere.
    e) depends upon the status of ozone in the atmosphere.

5) Earth's atmosphere absorbs and is heated by mainly which form of energy?
    a) radio
    b) infrared
    c) visible
    d) ultraviolet
    e) x-ray

6) Which of the following does <u>not</u> increase the amount of greenhouse gases in the atmosphere?
    a) burning of fossil fuels in automobiles
    b) certain agricultural activities including growing rice and raising cattle
    c) cutting down and burning trees in rain forests
    d) operation of nuclear power plants
    e) use of synthetic and manure fertilizers

7) Greenhouse gases affect Earth's overall surface temperature by
   a) destroying the ozone layer and allowing more sunlight into the atmosphere.
   b) altering how quickly plants carry out photosynthesis.
   c) concentrating smog and pollutants over populated cities.
   d) magnifying and focusing sunlight in the atmosphere.
   e) influencing the flow of energy through the atmosphere.

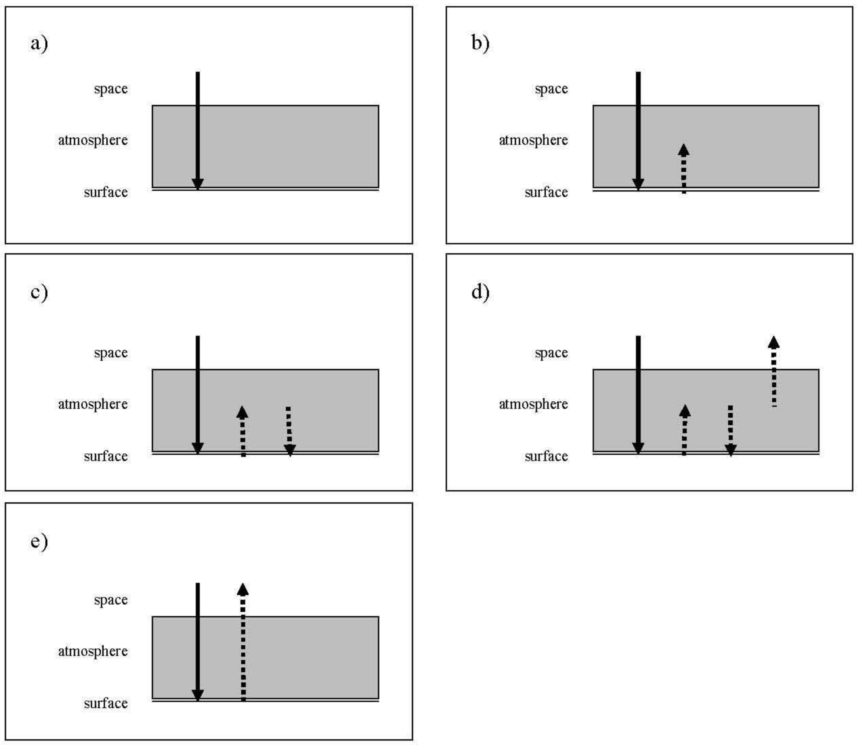
8) During the daytime, most of the energy bouncing or reflecting off Earth's surface is which of the following?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

9) During the daytime, Earth's surface mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

10) During the nighttime, Earth's surface mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

11) Which of the following most accurately describes the relationship between the greenhouse effect and recent human activity?
   a) Recent human activity is responsible for the creation of the greenhouse effect.
   b) The greenhouse effect has operated for most of Earth's history, but recent human activity appears to be enhancing the greenhouse effect.
   c) The greenhouse effect has operated for most of Earth's history, and recent human activity has had almost no influence on the greenhouse effect.
   d) The greenhouse effect has operated for most of Earth's history, but recent human activity appears to be decreasing the greenhouse effect.
   e) Recent human activity has stopped the greenhouse effect all together.

12) Each diagram below shows Earth's surface, the atmosphere, and outer space. The solid arrow represents incoming energy from the Sun that is absorbed by the surface. The dashed arrow represents energy that is radiated or given off by the surface. Select the diagram that best represents the transport of both incoming energy from the Sun and radiated energy from the surface.



13) Earth's atmosphere mainly gives off (radiates) which form of energy?
- a) radio
- b) infrared
- c) visible
- d) ultraviolet
- e) x-ray

14) Due to the greenhouse effect, Earth's overall surface temperature is
   a) warmer than otherwise because energy is temporarily trapped in the atmosphere.
   b) warmer than otherwise because energy is permanently trapped in the atmosphere.
   c) cooler than otherwise because less energy gets into the atmosphere.
   d) cooler than otherwise because energy leaves the atmosphere more quickly.
   e) the same temperature as it would be without a greenhouse effect.

15) What is your gender?
   a) Male
   b) Female

16) What year are you in university?
   a) Freshman
   b) Sophomore
   c) Junior
   d) Senior
   e) Other

17) Which of the following best characterizes your academic major?
   a) Undeclared
   b) Non-science
   c) Science
   d) Engineering / Math
   e) Other

18) Prior to this semester, which of the following best describes your previous coursework?
   a) I have never taken a class that covers the greenhouse effect.
   b) In high school, I took a class that briefly touched upon the greenhouse effect.
   c) In high school, I took a class that dealt extensively with the greenhouse effect.
   d) In college, I took a class that briefly touched upon the greenhouse effect.
   e) In college, I took a class that dealt extensively with the greenhouse effect.

19) Disregarding this course, have any of your other classes covered the greenhouse effect during this semester?
   a) Yes
   b) No

PLEASE STOP HERE IF YOUR DATE OF BIRTH IS AN ODD NUMBER.
THANK YOU FOR COMPLETING THIS SURVEY.

If the <u>DAY of your birth</u> is an <u>EVEN NUMBER</u>, please bubble in your answers to <u>Questions 21-39</u> on the scantron sheet provided. Take care to bubble in the right question number on the scantron. If the day of your birth is an odd number, please turn to Page 3.

21) The Sun mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

22) Which of the following is the most abundant greenhouse gas?
   a) carbon dioxide (CO_2)
   b) water vapor (H_2O)
   c) methane (CH_4)
   d) oxygen (O_2)
   e) ozone (O_3)

23) In addition to visible energy from the sun, Earth's surface mainly absorbs and is heated by which of the following forms of energy?
   a) infrared given off by the atmosphere
   b) ultraviolet given off by the atmosphere
   c) ultraviolet passing through the ozone layer
   d) infrared given off by cars and industry
   e) ultraviolet given off by cars and industry

24) The greenhouse effect influences the flow of energy
   a) into the Earth system from space.
   b) out of the Earth system into space.
   c) through the Earth system.
   d) both A and C.
   e) both B and C.

25) Earth's upper atmosphere (stratosphere) absorbs and is heated mainly by which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

26) Earth's lower atmosphere (troposphere) absorbs and is heated mainly by which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

27) Which one of the following is <u>not</u> a greenhouse gas?
   a) carbon dioxide (CO_2)
   b) water vapor (H_2O)
   c) methane (CH_4)
   d) oxygen (O_2)
   e) ozone (O_3)

28) With the greenhouse effect, which of the following most strongly affects Earth's overall surface temperature?
   a) heat released by factories and other industrial activities
   b) more sunlight passing through the ozone hole
   c) energy that is absorbed and then given off by gases in the atmosphere
   d) air pollution trapped in the atmosphere by gases
   e) gas molecules circulating in the atmosphere because hot air rises

29) Most of the energy bouncing (reflecting) off Earth's surface is in which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

30) Earth's surface mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

31) The greenhouse effect influences the average global surface temperature
   a) only during the day.
   b) only during the night.
   c) only during winter months.
   d) only during summer months.
   e) all the time.

32) If human civilization had never developed on Earth, would there be a greenhouse effect?
   a) Yes, the greenhouse effect is caused by naturally occurring gases in the atmosphere.
   b) Yes, the greenhouse effect is caused by plants giving off gases during photosynthesis.
   c) No, the greenhouse effect is caused by humans burning fossil fuels and releasing pollutants.
   d) No, the greenhouse effect is caused by humans depleting ozone in the atmosphere.
   e) No, there is no conclusive evidence that a greenhouse effect exists.

33) Greenhouse gases interact most strongly with which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

34) The greenhouse effect is
   a) a process that has operated for most of Earth's history to raise global surface temperature through interactions between gases and various forms of energy
   b) a process caused by plants that raises global surface temperature and increases humidity, creating conditions similar to those in a plant greenhouse.
   c) a recent increase in the average global surface temperature probably caused by burning of fossil fuels, industry, agriculture, and other human activities.
   d) a recent increase in average global surface temperature probably caused by depletion of the ozone layer which allows more ultraviolet light to reach the Earth's surface.
   e) a recent increase in average global surface temperature probably caused by natural processes including volcanic emission and changes in solar activity.

35) What is your gender?
   a) Male
   b) Female

36) What year are you in university?
   a) Freshman
   b) Sophomore
   c) Junior
   d) Senior
   e) Other

37) Which of the following best characterizes your academic major?
   a) Undeclared
   b) Non-science
   c) Science
   d) Engineering / Math
   e) Other

38) Prior to this semester, which of the following best describes your previous coursework?
   a) I have never taken a class that covers the greenhouse effect.
   b) In high school, I took a class that briefly touched upon the greenhouse effect.
   c) In high school, I took a class that dealt extensively with the greenhouse effect.
   d) In college, I took a class that briefly touched upon the greenhouse effect.
   e) In college, I took a class that dealt extensively with the greenhouse effect.

39) Disregarding this course, have any of your other classes covered the greenhouse effect during this semester?
   a) Yes
   b) No

PLEASE STOP HERE IF YOUR DATE OF BIRTH IS AN EVEN NUMBER.
THANK YOU FOR COMPLETING THIS SURVEY.

APPENDIX H: GECI.VB RESPONSE FREQUENCIES

This appendix provides the response frequencies for each of the items on Survey GECI.vB (see Appendix G). A table is provided for each item listing the number and percentage of students who selected each response option listed both pre- and post-instruction. As described in Section 3.1.2, the chemistry classes and NATS control group have been removed from the analysis presented in this appendix because these groups did not specifically treat the greenhouse effect. The results presented here comprise of students from ten Tier 1 NATS classes and three Tier 2 NATS classes (see Table 3.2).

See Appendix G and Section 3.1.2 for more details on survey administration.

GECI.vB * Q1 Crosstabulation

			Q1 A	Q1 B	Q1 C	Q1 D	Q1 E	Total
NATS	Pre	Count	67	366	177	52	4	666
		% within NATS	10.1%	55.0%	26.6%	7.8%	.6%	100.0%
	Post	Count	27	194	125	69	4	419
		% within NATS	6.4%	46.3%	29.8%	16.5%	1.0%	100.0%
Total		Count	94	560	302	121	8	1085
		% within NATS	8.7%	51.6%	27.8%	11.2%	.7%	100.0%

GECI.vB * Q2 Crosstabulation

			Q2 A	Q2 B	Q2 C	Q2 D	Q2 E	Total
NATS	Pre	Count	156	144	177	24	164	665
		% within NATS	23.5%	21.7%	26.6%	3.6%	24.7%	100.0%
	Post	Count	80	94	68	15	161	418
		% within NATS	19.1%	22.5%	16.3%	3.6%	38.5%	100.0%
Total		Count	236	238	245	39	325	1083
		% within NATS	21.8%	22.0%	22.6%	3.6%	30.0%	100.0%

GECI.vB * Q3 Crosstabulation

			Q3 A	Q3 B	Q3 C	Q3 D	Q3 E	Total
NATS	Pre	Count	59	333	179	69	25	665
		% within NATS	8.9%	50.1%	26.9%	10.4%	3.8%	100.0%
	Post	Count	15	190	95	110	8	418
		% within NATS	3.6%	45.5%	22.7%	26.3%	1.9%	100.0%
Total		Count	74	523	274	179	33	1083
		% within NATS	6.8%	48.3%	25.3%	16.5%	3.0%	100.0%

GECI.vB * Q4 Crosstabulation

			Q4 A	Q4 B	Q4 C	Q4 D	Q4 E	Total
NATS	Pre	Count	91	256	94	126	98	665
		% within NATS	13.7%	38.5%	14.1%	18.9%	14.7%	100.0%
	Post	Count	39	179	121	58	21	418
		% within NATS	9.3%	42.8%	28.9%	13.9%	5.0%	100.0%
Total		Count	130	435	215	184	119	1083
		% within NATS	12.0%	40.2%	19.9%	17.0%	11.0%	100.0%

GECI.vB * Q5 Crosstabulation

			Q5 A	Q5 B	Q5 C	Q5 D	Q5 E	Total
NATS	Pre	Count	13	140	40	461	12	666
		% within NATS	2.0%	21.0%	6.0%	69.2%	1.8%	100.0%
	Post	Count	12	155	74	175	3	419
		% within NATS	2.9%	37.0%	17.7%	41.8%	.7%	100.0%
Total		Count	25	295	114	636	15	1085
		% within NATS	2.3%	27.2%	10.5%	58.6%	1.4%	100.0%

GECI.vB * Q6 Crosstabulation

			Q6 A	Q6 B	Q6 C	Q6 D	Q6 E	Total
NATS	Pre	Count	34	331	41	128	132	666
		% within NATS	5.1%	49.7%	6.2%	19.2%	19.8%	100.0%
	Post	Count	10	195	16	111	87	419
		% within NATS	2.4%	46.5%	3.8%	26.5%	20.8%	100.0%
Total		Count	44	526	57	239	219	1085
		% within NATS	4.1%	48.5%	5.3%	22.0%	20.2%	100.0%

GECI.vB * Q7 Crosstabulation

			Q7 A	Q7 B	Q7 C	Q7 D	Q7 E	Total
NATS	Pre	Count	334	40	56	79	157	666
		% within NATS	50.2%	6.0%	8.4%	11.9%	23.6%	100.0%
	Post	Count	159	17	23	60	159	418
		% within NATS	38.0%	4.1%	5.5%	14.4%	38.0%	100.0%
Total		Count	493	57	79	139	316	1084
		% within NATS	45.5%	5.3%	7.3%	12.8%	29.2%	100.0%

GECI.vB * Q8 Crosstabulation

			Q8 A	Q8 B	Q8 C	Q8 D	Q8 E	Total
NATS	Pre	Count	49	141	148	307	21	666
		% within NATS	7.4%	21.2%	22.2%	46.1%	3.2%	100.0%
	Post	Count	23	120	147	123	6	419
		% within NATS	5.5%	28.6%	35.1%	29.4%	1.4%	100.0%
Total		Count	72	261	295	430	27	1085
		% within NATS	6.6%	24.1%	27.2%	39.6%	2.5%	100.0%

GECI.vB * Q9 Crosstabulation

			Q9					
			A	B	C	D	E	Total
NATS	Pre	Count	78	224	160	176	28	666
		% within NATS	11.7%	33.6%	24.0%	26.4%	4.2%	100.0%
	Post	Count	20	211	93	85	10	419
		% within NATS	4.8%	50.4%	22.2%	20.3%	2.4%	100.0%
Total		Count	98	435	253	261	38	1085
		% within NATS	9.0%	40.1%	23.3%	24.1%	3.5%	100.0%

GECI.vB * Q10 Crosstabulation

			Q10					
			A	B	C	D	E	Total
NATS	Pre	Count	106	337	82	99	39	663
		% within NATS	16.0%	50.8%	12.4%	14.9%	5.9%	100.0%
	Post	Count	30	284	39	57	9	419
		% within NATS	7.2%	67.8%	9.3%	13.6%	2.1%	100.0%
Total		Count	136	621	121	156	48	1082
		% within NATS	12.6%	57.4%	11.2%	14.4%	4.4%	100.0%

GECI.vB * Q11 Crosstabulation

			Q11					
			A	B	C	D	E	Total
NATS	Pre	Count	111	416	56	50	32	665
		% within NATS	16.7%	62.6%	8.4%	7.5%	4.8%	100.0%
	Post	Count	34	319	37	27	2	419
		% within NATS	8.1%	76.1%	8.8%	6.4%	.5%	100.0%
Total		Count	145	735	93	77	34	1084
		% within NATS	13.4%	67.8%	8.6%	7.1%	3.1%	100.0%

GECI.vB * Q12 Crosstabulation

			Q12					
			A	B	C	D	E	Total
NATS	Pre	Count	19	128	164	256	99	666
		% within NATS	2.9%	19.2%	24.6%	38.4%	14.9%	100.0%
	Post	Count	10	53	79	214	63	419
		% within NATS	2.4%	12.6%	18.9%	51.1%	15.0%	100.0%
Total		Count	29	181	243	470	162	1085
		% within NATS	2.7%	16.7%	22.4%	43.3%	14.9%	100.0%

GECI.vB * Q13 Crosstabulation

			Q13 A	B	C	D	E	Total
NATS	Pre	Count	92	217	96	217	44	666
		% within NATS	13.8%	32.6%	14.4%	32.6%	6.6%	100.0%
	Post	Count	34	206	64	102	11	417
		% within NATS	8.2%	49.4%	15.3%	24.5%	2.6%	100.0%
Total		Count	126	423	160	319	55	1083
		% within NATS	11.6%	39.1%	14.8%	29.5%	5.1%	100.0%

GECI.vB * Q14 Crosstabulation

			Q14 A	B	C	D	E	Total
NATS	Pre	Count	411	171	46	24	10	662
		% within NATS	62.1%	25.8%	6.9%	3.6%	1.5%	100.0%
	Post	Count	300	90	10	12	4	416
		% within NATS	72.1%	21.6%	2.4%	2.9%	1.0%	100.0%
Total		Count	711	261	56	36	14	1078
		% within NATS	66.0%	24.2%	5.2%	3.3%	1.3%	100.0%

GECI.vB * Q21 Crosstabulation

			Q21 A	B	C	D	E	Total
NATS	Pre	Count	6	55	57	441	8	567
		% within NATS	1.1%	9.7%	10.1%	77.8%	1.4%	100.0%
	Post	Count	6	103	111	193	1	414
		% within NATS	1.4%	24.9%	26.8%	46.6%	.2%	100.0%
Total		Count	12	158	168	634	9	981
		% within NATS	1.2%	16.1%	17.1%	64.6%	.9%	100.0%

GECI.vB * Q22 Crosstabulation

			Q22 A	B	C	D	E	Total
NATS	Pre	Count	369	55	31	76	38	569
		% within NATS	64.9%	9.7%	5.4%	13.4%	6.7%	100.0%
	Post	Count	290	69	11	18	26	414
		% within NATS	70.0%	16.7%	2.7%	4.3%	6.3%	100.0%
Total		Count	659	124	42	94	64	983
		% within NATS	67.0%	12.6%	4.3%	9.6%	6.5%	100.0%

GECI.vB * Q23 Crosstabulation

			Q23					Total
			A	B	C	D	E	
NATS	Pre	Count	111	80	316	47	13	567
		% within NATS	19.6%	14.1%	55.7%	8.3%	2.3%	100.0%
	Post	Count	179	61	144	25	5	414
		% within NATS	43.2%	14.7%	34.8%	6.0%	1.2%	100.0%
Total		Count	290	141	460	72	18	981
		% within NATS	29.6%	14.4%	46.9%	7.3%	1.8%	100.0%

GECI.vB * Q24 Crosstabulation

			Q24					Total
			A	B	C	D	E	
NATS	Pre	Count	75	90	107	200	95	567
		% within NATS	13.2%	15.9%	18.9%	35.3%	16.8%	100.0%
	Post	Count	40	75	73	123	103	414
		% within NATS	9.7%	18.1%	17.6%	29.7%	24.9%	100.0%
Total		Count	115	165	180	323	198	981
		% within NATS	11.7%	16.8%	18.3%	32.9%	20.2%	100.0%

GECI.vB * Q25 Crosstabulation

			Q25					Total
			A	B	C	D	E	
NATS	Pre	Count	25	188	42	291	22	568
		% within NATS	4.4%	33.1%	7.4%	51.2%	3.9%	100.0%
	Post	Count	8	155	32	213	6	414
		% within NATS	1.9%	37.4%	7.7%	51.4%	1.4%	100.0%
Total		Count	33	343	74	504	28	982
		% within NATS	3.4%	34.9%	7.5%	51.3%	2.9%	100.0%

GECI.vB * Q26 Crosstabulation

			Q26					Total
			A	B	C	D	E	
NATS	Pre	Count	29	169	139	215	17	569
		% within NATS	5.1%	29.7%	24.4%	37.8%	3.0%	100.0%
	Post	Count	16	210	93	85	10	414
		% within NATS	3.9%	50.7%	22.5%	20.5%	2.4%	100.0%
Total		Count	45	379	232	300	27	983
		% within NATS	4.6%	38.6%	23.6%	30.5%	2.7%	100.0%

GECI.vB * Q27 Crosstabulation

			Q27 A	B	C	D	E	Total
NATS	Pre	Count	9	148	133	105	174	569
		% within NATS	1.6%	26.0%	23.4%	18.5%	30.6%	100.0%
	Post	Count	16	79	93	133	92	413
		% within NATS	3.9%	19.1%	22.5%	32.2%	22.3%	100.0%
Total		Count	25	227	226	238	266	982
		% within NATS	2.5%	23.1%	23.0%	24.2%	27.1%	100.0%

GECI.vB * Q28 Crosstabulation

			Q28 A	B	C	D	E	Total
NATS	Pre	Count	50	171	149	163	34	567
		% within NATS	8.8%	30.2%	26.3%	28.7%	6.0%	100.0%
	Post	Count	41	97	190	76	10	414
		% within NATS	9.9%	23.4%	45.9%	18.4%	2.4%	100.0%
Total		Count	91	268	339	239	44	981
		% within NATS	9.3%	27.3%	34.6%	24.4%	4.5%	100.0%

GECI.vB * Q29 Crosstabulation

			Q29 A	B	C	D	E	Total
NATS	Pre	Count	77	164	114	174	39	568
		% within NATS	13.6%	28.9%	20.1%	30.6%	6.9%	100.0%
	Post	Count	27	177	103	96	11	414
		% within NATS	6.5%	42.8%	24.9%	23.2%	2.7%	100.0%
Total		Count	104	341	217	270	50	982
		% within NATS	10.6%	34.7%	22.1%	27.5%	5.1%	100.0%

GECI.vB * Q30 Crosstabulation

			Q30 A	B	C	D	E	Total
NATS	Pre	Count	84	216	138	91	39	568
		% within NATS	14.8%	38.0%	24.3%	16.0%	6.9%	100.0%
	Post	Count	24	254	58	64	14	414
		% within NATS	5.8%	61.4%	14.0%	15.5%	3.4%	100.0%
Total		Count	108	470	196	155	53	982
		% within NATS	11.0%	47.9%	20.0%	15.8%	5.4%	100.0%

GECI.vB * Q31 Crosstabulation

			Q31					Total
			A	B	C	D	E	
NATS	Pre	Count	23	22	20	20	484	569
		% within NATS	4.0%	3.9%	3.5%	3.5%	85.1%	100.0%
	Post	Count	25	19	20	8	342	414
		% within NATS	6.0%	4.6%	4.8%	1.9%	82.6%	100.0%
Total		Count	48	41	40	28	826	983
		% within NATS	4.9%	4.2%	4.1%	2.8%	84.0%	100.0%

GECI.vB * Q32 Crosstabulation

			Q32					Total
			A	B	C	D	E	
NATS	Pre	Count	156	96	173	109	34	568
		% within NATS	27.5%	16.9%	30.5%	19.2%	6.0%	100.0%
	Post	Count	233	53	76	42	9	413
		% within NATS	56.4%	12.8%	18.4%	10.2%	2.2%	100.0%
Total		Count	389	149	249	151	43	981
		% within NATS	39.7%	15.2%	25.4%	15.4%	4.4%	100.0%

GECI.vB * Q33 Crosstabulation

			Q33					Total
			A	B	C	D	E	
NATS	Pre	Count	20	140	69	320	19	568
		% within NATS	3.5%	24.6%	12.1%	56.3%	3.3%	100.0%
	Post	Count	22	173	50	162	7	414
		% within NATS	5.3%	41.8%	12.1%	39.1%	1.7%	100.0%
Total		Count	42	313	119	482	26	982
		% within NATS	4.3%	31.9%	12.1%	49.1%	2.6%	100.0%

GECI.vB * Q34 Crosstabulation

			Q34					Total
			A	B	C	D	E	
NATS	Pre	Count	140	94	194	130	8	566
		% within NATS	24.7%	16.6%	34.3%	23.0%	1.4%	100.0%
	Post	Count	188	51	113	47	11	410
		% within NATS	45.9%	12.4%	27.6%	11.5%	2.7%	100.0%
Total		Count	328	145	307	177	19	976
		% within NATS	33.6%	14.9%	31.5%	18.1%	1.9%	100.0%

APPENDIX I: REQUEST FOR INTERVIEW VOLUNTEERS

Students were recruited from one of the planetary science classes participating in the Fall 2005 administration of GECI.vB. In this class, the researcher explained to students that he was seeking 12-20 volunteers willing to participate in a 30-60 minute interview regarding the topics covered in the greenhouse effect survey that students had taken at the beginning of the semester. Questions on this interview would focus on student explanations of their reasoning behind their answers on this survey. It was emphasized to students that the interviews were completely voluntary and that there was no obligation to participate. All class members were given a copy of the Recruitment Letter reproduced on the following page and asked to return the bottom half of the document to either the researcher or their instructor if they were interested in being considered for an interview.

Recruitment Letter: Voluntary Student Interview Regarding the Greenhouse Effect

At the beginning of this semester, members of your class volunteered to complete a survey regarding the concept of the Greenhouse Effect. To validate and better understand student responses to this survey, the Principle Investigator, John Keller, is asking for students to volunteer for a 30-60 minute student interview regarding the questions and content of this survey. If you are interested in volunteering for this research project, we ask that you complete and return the bottom half of this document providing contact and scheduling information to set up an interview. You may or may not be selected to participate in an interview based upon a random selection process used to select 12-20 volunteers from those who return the below form. An attempt will be made to interview an equal number of male and female students.

The only selection criteria for this project are that you are enrolled in this general education science course for non-science majors, are 18 years of age or older, and completed the Greenhouse Effect survey given earlier this year. No compensation will be provided to you, but your responses will be very valuable to the research efforts of the Principle Investigator who is trying to obtain a better understanding of student thinking regarding the Greenhouse Effect.

Interviews will be conducted in the Kuiper Space Science building in one of two conference rooms (Room 301 or 309). Interviews will last between 30-60 minutes and will be audiotaped. Questions during the interview will involve the reasoning behind your responses to questions that you have already seen on the Greenhouse Effect survey described above. There will also be 2-3 additional questions regarding your understanding of the Greenhouse Effect and the topic of Global Climate Change.

If you are interested in being considered as a volunteer for this project, please complete and return the bottom section of this document to either the Principle Investigator, John Keller, or your instructor. If you have any questions regarding this research study, you can contact Mr. Keller at (520)621-1632.

Thank you for your time and consideration,

John M. Keller
PhD. Candidate

-- separate here --

Name: ____

E-mail address: _______________________________________

Daytime Phone Number: _________________________________

Gender: M F

Course Professor: _____________________________________

Did you complete a survey on the Greenhouse Effect at the beginning of this semester? Y N

Circle the times below that would work best scheduling the 30-60 minute interview.
Cross off those times that do not work well for you.

Mon morning (9AM-noon)	Tues morning (9AM-noon)	Wed morning (9AM-noon)	Thurs morning (9AM-noon)	Fri morning (9AM-noon)
Mon afternoon (1PM-5PM)	Tues afternoon (1PM-5PM)	Wed afternoon (1PM-5PM)	Thurs afternoon (1PM-5PM)	Fri afternoon (1PM-5PM)

APPENDIX J: INTERVIEW OUTLINE SAMPLE

Students who volunteered to be interviewed were randomly selected by the researcher with attention towards setting up interviews with an equal number of male and female participants. Selected students were contacted via e-mail and interview dates and times that were convenient for each student were arranged. All interviews occurred in either Room 301 or 309 of the Kuiper Space Science Building. During a pre-interview screening, the Informed Consent Form was discussed and signed by each student and the PI. The sample outline below provides an overview of the nature of each interview. Students were frequently asked to elaborate on their answers and each interview varied slightly in terms of the sequence and amount of time spent on each question. Interviews were audio-taped, transcribed, and summarized by the researcher.

INTRODUCTORY DESCRIPTION OF GREENHOUSE EFFECT

The student was first asked to give his or her own description of the greenhouse effect in an attempt to get a sense of his or her understanding and terminology related to the greenhouse effect before going over the survey content items.

- Describe for me in as much detail as possible what you think the greenhouse effect is. Feel free to provide a drawing to go along with your description if that helps.

Often, a student would introduce one of the following terms in their description: ozone depletion, ozone hole, global warming, or pollution. In some cases, the researcher followed upon this before going over the survey content items.

- You mentioned one or two terms in your description that I would like to follow up on. I'm going to list 3-4 terms that may be related or unrelated: greenhouse effect, ozone depletion, global warming, air pollution. Describe for me what each of these is and how they are similar and different.

STUDENT BACKGROUND INFORMATION

Following the previous introductory questions, the research determined which survey form the student had completed at the beginning of the semester: students with odd days of birth completed GECI.vB1 with Items 1-19, students with even days of birth completed GECI.vB2 with Items 21-39. The student was then asked to turn to the last four questions of the appropriate survey and asked to provide background information listed on these questions.

- Year in school
- Academic major
- Previous classroom experiences with the greenhouse effect in university or before
- Additional classes covering the greenhouse effect during the current semester

SURVEY CONTENT ITEMS AND EXPLANATIONS

Next the researcher explained to the student that they would take ~20 minutes to go over each of the fourteen content items found on the survey. For each, he would like the student to read the question silently and chose the best answer for the question based upon the student's current understanding. The student would then be asked to explain the reasoning behind his or her choice and also to describe why they had not chosen certain options. It was explained that questioning by the researcher was not intended to indicate that the student had given a correct or incorrect answer, but rather to probe further into the student's reasoning behind certain choices.

The researcher and student then proceeded to go over Items 1-14 or Items 21-34, depending upon which survey the student had completed earlier in the semester. Survey items were rarely skipped and only in the interest of time. Types of follow-up questions included:

- Why do you think that?
- Can you explain your reasoning behind that choice?
- Can you elaborate on your response?
- Can you draw me a picture of what you are describing?
- If you had to make a guess, does one option stand out as being more likely?
- Which options are least likely or seem like ridiculous answers?
- Why did you eliminate these options?
- If the question allowed you to "choose all that apply" which options would you select?
- How would you rank these in order from most likely to least likely?
- How is your answer to this previous question related to your answer on this question?

In the interest of time and/or to clarify certain questions, the researcher often provided the following contextual information to students for the following items:

- Items 8-10: These three questions are somewhat related. The first two ask about energy bouncing and being given off by the surface during the daytime. The last deals with energy being given off by the surface during the nighttime.
- Item 12: Let me explain these diagrams to you for a second. Each diagram shows the surface, atmosphere, and space. The solid arrow represents incoming energy

from the Sun that is absorbed by the surface. The dashed arrows represent energy that has been radiated or given off by the surface.

- Item 24: Can you describe for me what you think we meant by "the Earth system?"
- Items 25-26: The first of these deals with the upper atmosphere. The second deals with the lower atmosphere.
- Items 29-30: The first question asks about energy that is bouncing or reflecting off the surface. The second deals with energy that is being given off by the surface.

SUMMARY DESCRIPTION OF GREENHOUSE EFFECT

After going over the survey content items, each interview was concluded with the following questions:

- We've now gone over all of these questions about the greenhouse effect. Can you describe to me one more time in your own words what you think the greenhouse effect is. Again, feel free to draw a diagram if that helps.
- I'm going to write down a few terms that you have used or that you may have heard: ozone depletion, greenhouse effect, global warming, and pollution. Each of these may be related or they may be different. Can you describe for me what you think each is and how they are similar and/or different from each other?

TERMINATION OF INTERVIEW

Following these questions, the audio-tape recorder was turned off and each student was given a chance to ask the researcher questions about the interview.

APPENDIX K: INTERVIEW SUMMARIES

Provided below are detailed summaries of each of the interviews conducted during Fall 2005. All interviews were first transcribed verbatim. The audio-tapes, transcriptions, and student diagrams were then used to create the summaries below with attention to statements and descriptions provided by students illustrating student thinking about the greenhouse effect and the greenhouse effect survey. Student background information is presented at the beginning of each summary even though this information was typically acquired after students had provided an introductory description of the greenhouse effect (see APPENDIX J). In some cases, related survey content items have been summarized together although they were discussed during different portions of the interview. Copies of sketches made by both students and the interviewer are provided at the end of each interview summary.

The interviews presented here were conducted after the administration of the pre-instruction GECI.vB (see Appendix G) but before direct instruction on the greenhouse effect and subsequent administration of the post-instruction survey.

Interview participants are listed below in chronological order of the interviews. All names are pseudonyms provided by each student.

1. Melissa (with 1 student sketch)
2. Rebecca
3. Kevin (with 1 student sketch)
4. Paul (with 1 student/researcher sketch)
5. Conan (with 1 student sketch)
6. George (with 1 student sketch)
7. Raoul (with 1 student sketch and 1 student/researcher sketch)
8. Farah (with 1 student sketch)
9. Elizabeth (with 1 student sketch and 2 student/researcher sketches)

Interview #1 with Melissa on September 26, 2005 at 3PM

Melissa was a freshman in her first semester at the university with a declared major in political science. In high school, she had never taken a class that dealt with the greenhouse effect. However, she had participated in an extracurricular environmental club led by a parent advisor that had discussed the greenhouse effect several times after school over the course of a couple of months. Unlike the other interviews, there were two interviewers present rather than just one. Both interviewers were participants on the interview human subjects proposal. Melissa was more quiet and non-committal in her responses than several of the other interviewees. She tended to give shorter answers and spent more time affirming questions or statements made by the interviewers rather than freely volunteering her own descriptions.

Melissa had completed GECI.vB2, and the interview began by going over Items 21 through 34 on this survey. She thought that the Sun mainly gives off visible energy based upon "the fact that you can see the Sun, you can see the light." When asked if she had to make a second guess, she selected ultraviolet because she knew "all about how UV rays cause Sunburns and things like that, so it must be at least somewhat of it [sunlight]."

Midway through the interview, however, Melissa changed her answer to the above question to ultraviolet when she came to Items 25 and 26. She had trouble distinguishing between the stratosphere and troposphere on these questions, but thought that ultraviolet energy was mostly responsible for heating both. "Same reason as 21 . . . there obviously is a lot of ultraviolet energy given off by the Sun, and I really didn't know, like I said, the difference between the upper and lower atmosphere." When asked how she learned that there is more ultraviolet coming from the Sun, she referred to the introductory science class she had been recruited from for the interview. Based upon her responses, it seemed that the discussions in this class regarding wavelengths, frequencies, and energies of electromagnetic radiation reinforced the idea that the Sun must be giving off a lot of ultraviolet energy.

Melissa was confident that carbon dioxide is a greenhouse gas. She was largely unsure about the other four selections listed in Item 22 and suggested that all of them may be greenhouse gases. When pressed, she chose ozone as the second best choice. For Item 27, she chose either oxygen or water vapor as most likely to not be a greenhouse gas based upon things she had learned in her after-school environmental club.

Melissa's difficulty describing the Earth system for Item 24 raised concerns that the question may be too abstract and generalized. She originally chose that the greenhouse effect influences the flow of energy both out of and through the Earth system. However, she provided very non-committal responses, including the following:

> Now that I think about it more, I don't really know what through the Earth's system would mean . . . the energy would be staying in the Earth's system, or more of it, because of the greenhouse effect, and I guess therefore it would have to move through the Earth's system to . . . be able to leave it.

She attempted to draw a picture of energy leaving the Earth system and expressed that "some [of the energy] would make it through, but not as much, because of the greenhouse effect." Later she expressed her gut instinct that the greenhouse effect also influences the amount of energy flowing into the atmosphere, which was different from her initial answer.

Responses to Items 25-27 are discussed above. Before selecting a response to Item 28, Melissa initially expressed confusion about the correct response for the question, that energy is absorbed and then given off by greenhouse gases. She "didn't quite understand how that would work, like what gases would absorb it and then give it off and how . . . It seems like it could be a viable choice, but I just didn't understand it." When asked whether another choice seemed more viable, she gravitated towards more sunlight passing through the ozone hole because of "things you hear, like on the news, about a hole in the ozone layer growing bigger and more energy is coming in and, you know, melting polar ice caps and things like that, global warming kind of." Finally, Melissa also suggested that all of the options to this question may be viable. "I would say all of them, but then I would, again, with Answer C [the correct answer], I don't exactly understand it."

Melissa was unsure about the types of light mainly reflected and radiated from Earth's surface (Items 29 and 30) but suggested that it is probably the same type of light for both. She hesitantly guessed that ultraviolet might be the proper response for both based upon her previous answers, but had difficulty distinguishing between reflection and radiation. She was much more confident in answering Item 31 that the greenhouse effect influences temperatures all of the time. She felt that the greenhouse effect is always present and therefore would always be influencing temperatures.

Through Items 32 and 34, Melissa expressed a belief that the greenhouse effect is a natural process that has been exacerbated through human activities. She felt that ozone depletion and burning fossil fuels were a part of the greenhouse effect, but because they were listed as separate options on Item 32, this excluded selecting either answer because the choices were "too narrow" or too mutually exclusive. On Item 34, she selected a slightly different answer (C – that the greenhouse effect is due to a recent increase due to burning of fossil fuels, . . . and other human activities). She independently recognized that this answer contradicted her answer to Item 32. Through the discussion, she expressed that the phrase "and other human activities" helped broaden the scope of this selection option beyond the other choices. This, along with the phrase "burning of fossil fuels," was a primary motivator for her selection. She hesitated to select answers A and E for Item 32 because they did not involve human activity at all. "There would be some effect that humans would have on it so it wouldn't just be natural processes." Melissa's mental model is more focused on the human enhancement of the greenhouse effect than the natural background greenhouse effect.

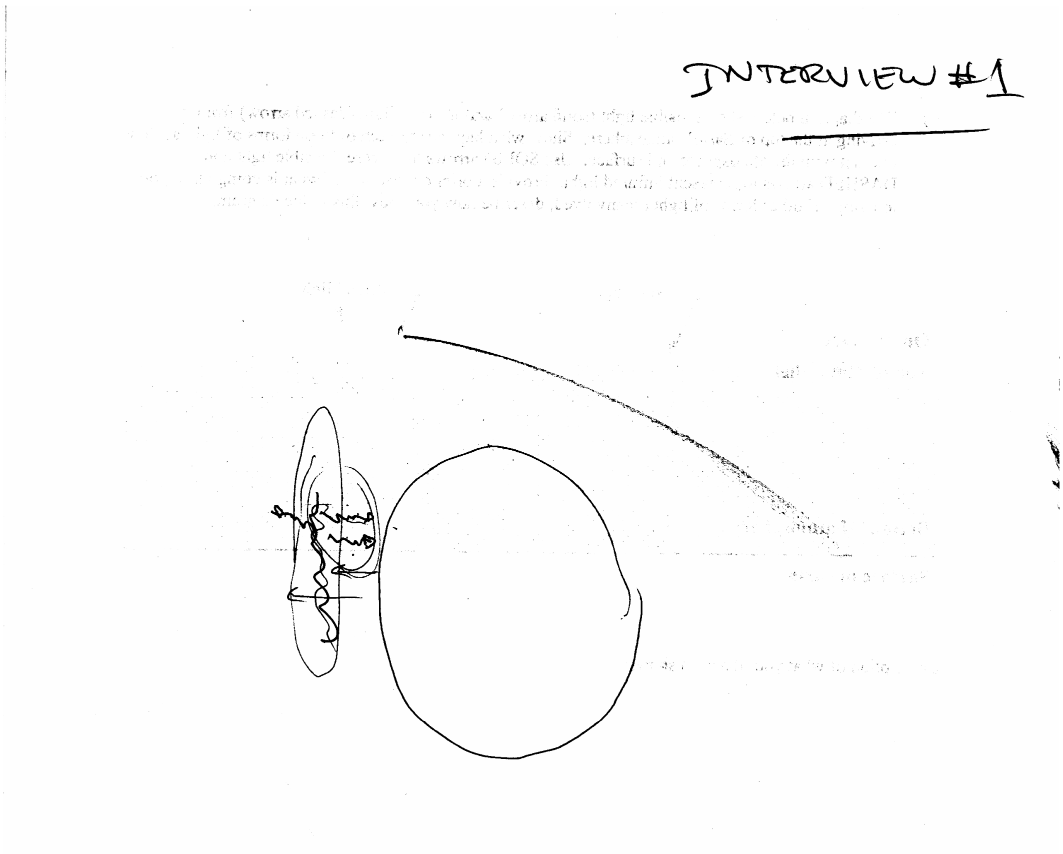
After going through all fourteen questions on the survey, Melissa was asked to provide an explanation of what the greenhouse effect is. Her response reveals her connection between ozone depletion and the trapping of pollution and energy in Earth's atmosphere:

> I guess I would have said something about the ozone layer and the ozone hole and it allows more light and more energy to reach the Earth's atmosphere, and then I would've talked about how, how pollutants and other products of human activity, those kinds of energy are being trapped in by certain gases in the atmosphere.

In this response, she touched upon an understanding that something is trapped by greenhouse gases, but she mixes the concepts of pollution, energy, and gases as the thing being trapped. Previously in the interview, she had described pollution as "things like greenhouse gases, like carbon dioxide, that are emitted from cars and factories and other things, that, obviously, have heat and energy, and like it grew kind of, um, and some of them do escape out of the atmosphere, but some of them are trapped in the atmosphere by gases." She clarified here that by "pollution" she meant greenhouse gases. In her description, the greenhouse gases are the things that are trapped, rather than heat and energy being trapped by greenhouse gases. These greenhouse gases "have heat and energy" at the time of their release as pollution.

She was also asked whether she could distinguish between the terms greenhouse effect, global warming, global climate change, and ozone depletion. She stated "Not a firm one. I know there is a difference and I know they're all related in some way, but I wouldn't know how to describe this." She was most comfortable with the term global warming, which she described as: "an increase in average surface temperature on the Earth caused by things like the greenhouse effect and ozone depletion. I would include those two terms in my definition of global warming . . . and the causes of global warming."

The interviewer ended by asking Melissa if she had any questions. The transcription recorder was turned off at that time.


INTERVIEW #1

Interview #2 with Rebecca on September 27, 2005 at 11AM

Rebecca was a freshman non-science major. She had never taken a class previously that covered the greenhouse effect, and she was not enrolled in other classes that would deal with the topic that semester besides the recruitment class. She had low confidence in her science abilities and provided disclaimers throughout the interview like "I'm not a very science-minded person." However, she provided clear and confident responses and was very articulate.

At the outset of the interview, Rebecca was asked to describe what she thought the greenhouse effect is and to include a drawing if she wanted to. She declined on the opportunity to draw, but provided a thorough description of the greenhouse effect, which:

> has something to do with the pollutants and everything that we, as humans, produce are eating up the ozone layer that pretty much surrounds the Earth. I don't know exactly what it does, but the problem with it is that the harmful rays from the Sun, UV rays, etc., are getting in easier because there's not that protective layer around, and, and I'm assuming that would make us hotter, and, yeah, that's about it.

She followed up on this statement by confirming that UV rays "are harmful to your skin" and "increase the overall temperature of the Earth." More of the UV rays get through the ozone layer because of "harmful gases and pollutants that are in the air that are damaging the ozone layer, creating holes." She could not provide examples of the pollutants, but assumed that "cars, factories, and anything that produces air pollution" were sources. She also clarified that by pollution she meant both visible pollution "like smog and such" and invisible pollution, and expressed that both forms of pollution cause the greenhouse effect.

Interestingly, during the middle of the interview when answering Items 25 and 26 about the main form of energy heating Earth's stratosphere and troposphere, Rebecca did not make the same connection between ultraviolet light and heating of the Earth's atmosphere. She "could not even make an educated decision" and after being reminded of her answer above, she still had no idea if the "Sun radiating ultraviolet light means the ultraviolet is also heating up the Earth." It is unclear why Rebecca had difficulty transferring her connection between ozone depletion and temperature increases to Items 25 and 26. However, when she got to Item 28, Rebecca returned to her initial explanation that the Earth's overall surface temperature is most affected by more sunlight passing through the ozone hole. When asked which were the least likely options for this item, she selected Option D (air pollution trapped in the atmosphere) and Option E (gas molecules circulating through the atmosphere). She does not appear to have a trapping of gases model for the greenhouse effect, but rather an energy flow through the ozone hole model.

Following the initial prompt about the greenhouse effect, the interview turned to a discussion of Items 21-34 on GECI.vB2. She chose ultraviolet light as the main form of energy given off by the Sun "mostly because it's the one that I know the most about . . . in terms of obviously like Sunscreen and things, it has to be present in our atmosphere in order for me to have heard about it." She also referred to discussing the forms of electromagnetic energy in the introductory science class from which she was recruited for the interview. She remembered her instructor "saying that out of all the different forms of light, infrared and things like that, that exist on the Earth, visible light is a very small percentage." This appears to have reinforced the idea that ultraviolet light might be a larger percentage.

Rebecca utilized similar reasoning to select that greenhouse gases interact most strongly with ultraviolet light on Item 33 when she explained, "It's the one of the ones I know most about, and because from what I've heard about greenhouse gases and holes in the ozone, that's the biggest problem when it comes to depleting the ozone is the increase in ultraviolet rays getting through. I don't know about interactions, so much as just, like, that's the biggest problem with it."

Rebecca chose carbon dioxide as the most abundant greenhouse gas "because it seems that everything gives off, that humans give off, carbon dioxide. Even plants during photosynthesis, cars and factories, everything seems to give off CO_2." She had not heard as much about things giving off the other gases. For Item 27, she chose ozone as the gas that is not a greenhouse gas because she had "heard that greenhouse gases are damaging the ozone, so logically, ozone could not be a greenhouse gas if what I've heard is correct."

When selecting infrared light given off by cars and industry as her answer for Item 23 regarding the main heat source for the surface of the Earth, Rebecca constructed her response based upon a number of things she had recently learned in the intervention class. She had seen a demonstration with an infrared camera and knew that hot things give off infrared light. She had also learned about the second law of thermodynamics and "how everything just kind of ends up trying to even out heat-wise." She was "not really sure in what forms cars and industry would give off ultraviolet." When asked about why she had not chosen infrared light given off by the atmosphere, she described a model in which heat from the atmosphere only goes one direction, into space:

> Because of the demonstration you did, the picture I have in my head is heat would disburse around itself versus, like, so if you had two objects and one was hot, or like a very hot object in a room, then it would eventually cool off and heat up the room a little bit more. But, if the atmosphere is giving off heat, then I would imagine that the Earth is losing heat, and space is getting warmer . . . obviously, not very much [warmer] because it's large.

She could not imagine anywhere else heat from the atmosphere could be going other than space.

While she could not imagine heat flowing from the atmosphere back to the surface, Rebecca did have a two way model regarding the flow of energy between the Earth system and space. She described her vision of the Earth system as being a giant foam globe with trees, mountains, cars, cities, people, water, etc. The Earth system also included air and clouds, although she could not see the air in the model because it would be invisible. She wanted to choose options A and C for Item 24, but also wanted to add option B:

> I'd imagine if it's affecting things going in, then it would also be affecting things going out, which is why I wanted to say B, because I keep hearing there are holes in the ozone layer, and so I would assume that if there's a hole, then it's a two-way, in-and-out system.

For Items 29 and 30 which deal with reflection and radiation of light, Rebecca was initially confused by the question, but after the interviewer explained that all the choices were forms of light and could all be reflected or radiated, she confidently selected the right answers and provided the following explanations:

> I would imagine visible light would be the one bouncing because . . . that's what you see, that's why we see people, that's why we see objects, because there's visible light bouncing off of them. Um, versus something radiating something would be infrared, because infrared is essentially heat, from what I know. So we all give off heat.

Providing insight into why some students chose that the greenhouse effect operates all of the time, Rebecca explained that it is always daytime somewhere on the planet and the Sun is present year round. When asked if she felt the greenhouse effect is more of a local or global phenomenon, she suggested that the greenhouse effect is "probably stronger in some places than others, depending on the time of year, but it's probably always present everywhere and then disburses."

Regarding Rebecca's distinction between the greenhouse effect and global warming, Rebecca indicated her opinion regarding whether the greenhouse effect is real, stating "I've heard arguments that the greenhouse effect does not actually exist, but I've also heard rumors that Neverland is on the moon, so I'm not sure where that argument stands." She also distinguished between the natural greenhouse effect and human-induced greenhouse effect. Although she selected Option B for Item 32 that plants give off gases during photosynthesis, her choice was based on correct reasoning "that were humans not to exist, . . . the greenhouse effect would still occur because these gases do naturally occur in nature. However, humans are reproducing them at a mass rate." Unfortunately, the interviewer failed to follow up on this and ask her why she had not selected the correct Option A which has the same language as above.

Item 34 involves whether the greenhouse effect is a recent phenomenon or a process that has operated throughout Earth's history. Rebecca firmly stated that Option B was not the correct answer and that she wanted to pick D (recent phenomenon due to ozone depletion), but correctly chose Option A. The word "recent" turned her away from selecting Options C through E, even though she would have chosen these if the word "recent" had been removed. While Rebecca's understanding of the greenhouse effect involves ozone depletion, she holds an even more firm mental model that the greenhouse effect is "something that's probably occurred very slowly over time, it's only increased more recently with the increase in technology."

At the very end of the interview, Rebecca was asked to re-explain the greenhouse effect and gave an explanation similar to the discussion above involving ozone depletion and more energy entering Earth's atmosphere:

> I'm pretty much gonna have to go with the same thing, I guess. Um, just the gases that are emitted within the Earth, um, from cars, industry, pollutants, um, also from plants and, I'm gonna, actually, I will add one thing, I'm gonna go with the volcanoes on this one, there are also emitting gases that are depleting the ozone layer and causing holes that are letting more energy in, sunlight and UV rays and such through, to the Earth that are not only damaging, um, skin and things like that, but also heating up the Earth in general.

She also reiterated that "the gases that were on the Earth before humans were damaging, but not to the same extent, so now it's becoming a bigger problem because holes inside the ozone layer are getting bigger and more common than they were in the past."

The interviewer then listed three different terms commonly used by scientists and the media: ozone depletion, greenhouse effect, and global warming. Rebecca quietly restated the last term as a question to herself, "Global warming?" Before the interviewer could ask her to describe each of these, she enthusiastically stated "You want me to connect them don't you? . . . I have this awesome idea going!" She then presented the following insightful description:

> What I'm thinking is the ozone depletion has to do, once again, with gases and things that you have in the ozone layer. Um, greenhouse effect would be about the gases, I don't know if I said this before, but the gases have, not gases, what am I talking about, um, UV rays and such, have a certain amount of energy and by the time they hit the Earth, they, and bounce back off, go back out in space they don't have enough energy to get back out, so they end up just staying, which would be the greenhouse effect, so, all the heat and energy just ends up staying in the Earth, instead of going back out to holes in the ozone layer, um, which, in turn, creates global

> warming cause there's more heat and energy bouncing around the atmosphere than there normally would have been.

This final response opened up a whole set of mental doors that could have been probed. Why don't reflected rays have enough energy to get back out? Where do they stay? If there weren't holes in the ozone layer would energy be able to leave the Earth? It was almost as if the addition of the term "global warming" provided a new label that Rebecca wanted to use to re-describe several of her previous answer. Unfortunately, there was only time remaining to clarify one of these: Is the greenhouse effect the same as ozone depletion? She stated that she thought the greenhouse effect is "more of an effect of ozone depletion, hence greenhouse effect. . . . I was definitely kind of pulling it all together when I first explained it." The interview was ended at this point due to scheduling constraints.

Interview #3 with Kevin on September 27, 2005 at 11:45AM

Kevin was an undeclared freshman who had briefly touched upon the greenhouse effect during high school. He described that his AP biology teacher “always talked about global warming . . . but never really talked about the greenhouse effect.” He spoke freely throughout the interview and used the word “like” a lot; this word has been removed from several of the quotes below. He had completed GECI.vB2 and so the interview focused on Items 21-34 of the survey.

Kevin started his explanation of the greenhouse effect by drawing a representation of the ozone layer and describing that carbon dioxide fumes eat the ozone layer. He next mentioned that CFCs and related products (Styrofoam and aerosol cans) heat up the atmosphere and that this is like global warming. He next mentioned that this heating is like a greenhouse, drew a picture of a box to represent a greenhouse, and explained that the Sun comes in and the greenhouse “gets heated up and then the heat just keeps on like re-circulating.” In a similar manner, “the atmosphere is keeping heat in.” When asked if carbon dioxide, CFCs, aerosol cans, and Styrofoam do the same or different things to heat the atmosphere, he said they do different things, stating, “the car and outside fumes like actually heat it up and then the CFC’s they actually eat the ozone layer.” Even though he explained that these are different processes, however, he thought that they were all part of the greenhouse effect.

Turning to the survey questions, Kevin thought that the Sun “gives off at least infrared and visible and ultraviolet, but mostly visible.” He also selected carbon dioxide as the most abundant greenhouse gas because “that’s what I always here when you hear about the greenhouse effect.” He had heard about the other gases, but didn’t really know if they were actually greenhouse gases. For Item 27, he selected water vapor as not being a greenhouse gas based upon that observation that water vapor isn’t “that high up . . . because clouds aren’t that high.” To Kevin, the other gases were more likely to be higher up in the atmosphere and this was important. For Kevin, the greenhouse effect is a process occurring primarily in the ozone layer and other high layers of the atmosphere.

He selected Option C for Item 23, that the surface is mainly heated by ultraviolet light passing through the ozone layer. He chose this option over the choices involving atmosphere heat because although the atmosphere gives off energy, he "always thought it went back into space, not down to Earth." Similarly, heat from cars and industry would go into the atmosphere and then, presumably, into space rather than heating the surface. He thought that Option E was the least likely answer because heat given off by cars and industry would more likely be in the form of infrared than ultraviolet light. The Sun is the "main giver of energy" in Kevin's mind, not the atmosphere or surface processes.

Similar to other interviewees, he thought that the greenhouse effect influences the flow of energy into, out of, and through the atmosphere and would have preferred an Option F ("All of the above") over the choices provided for Item 24.

Items 25 and 26 deal with heating of the troposphere and stratosphere. Kevin distinguished between the types of energy absorbed by each layer, explaining "the ultraviolet rays would be, like, absorbed better by the stratosphere, and so then they wouldn't pass through to the troposphere, which would be heated up by like the visible light." When asked about the temperature of the stratosphere, he described that ozone depletion would tend to cool the stratosphere and heat Earth's surface.

On Item 28, Kevin re-affirmed his belief that ultraviolet light passing through the ozone hole is a primary source of heat for Earth's atmosphere. When asked about the other selections, he utilized the concept of urban islands to select heat released by factories and other industry as a possibility. "I've always thought that like lots of concrete, for some reason, . . . increases the surface temperature, 'cause it like gets absorbed during the day and then goes off during night." The interviewer pressed further on this point to clarify the following aspects of Kevin's thinking: 1) the energy given off by concrete is in the form of infrared energy, 2) this energy is given off by the concrete during the night into the atmosphere. Again, he was unclear if this energy in the atmosphere could then heat the Earth surface more. His model involved the heat from the concrete heating the surface rather than atmospheric heat being re-radiated back down to Earth.

Kevin wanted to draw a picture to explain his answers to Items 29 and 30 about energy reflecting and radiating off Earth's surface. He first drew a circle for the Sun and a line for the surface of the Earth. He then drew a ray of light reflecting off the surface of the Earth following the law of reflection. For radiation, he drew a ray of light down to the Earth's surface and then drew three wavy lines off to the right of the Sunbeam coming off the surface. His picture definitely shows reflecting light as a continuous beam and the radiating light as being separate from the absorption or heating event. He had a hunch that most of the energy reflecting was visible light but couldn't pin down a basis for this hunch. He was more sure about infrared light radiating from the surface because "heat gets absorbed and then goes off later." This latter response was similar to his reasoning in the concrete discussion described above. He did not think that visible light was radiated from the surface of the Earth because you can't see the Earth surface "when it's dark."

While Kevin answered that the greenhouse effect influences average global temperatures all the time for Item 31, he also volunteered a model of local heating rather than global heating. He did not think that global temperatures were increasing everywhere. "Sometimes you hear it only goes up in certain places? So it [increasing surface temperature] probably happens there all the time, but not everywhere all the time."

He selected both human burning of fossil fuels and humans depleting the ozone layer as causes for Item 32 and stated that his definition of the greenhouse effect includes "both the ozone layer and global warming." He did not think that the greenhouse effect would be happening without humans, but he was not sure. When asked if greenhouse gases could form naturally, he suggested that plants give off carbon dioxide but not CFCs. (Note that later on in the interview, Kevin realized independently that plants "breathe in" more carbon dioxide than they give off.) On Item 34, he selected Option D – the greenhouse effect is a recent increase due to ozone depletion – but expressed confusion about the importance of natural climate change at this point. "The thing I've never understood is if the greenhouse effect includes surface temperature changes, then doesn't it kind of happen naturally, like, with ice ages, too? So, I think it's maybe it'd be a different type of thing, but maybe they're kind of the same. I don't know. I always wondered, like, wouldn't that happen naturally?" This served as a springboard for asking Kevin to clarify the difference between greenhouse gases, ozone depletion, and global warming. He provided the following description with a clear definition of ozone depletion, a fuzzy understanding of the greenhouse effect, and a belief that both lead to global warming which involves increases in surface temperature and other effects:

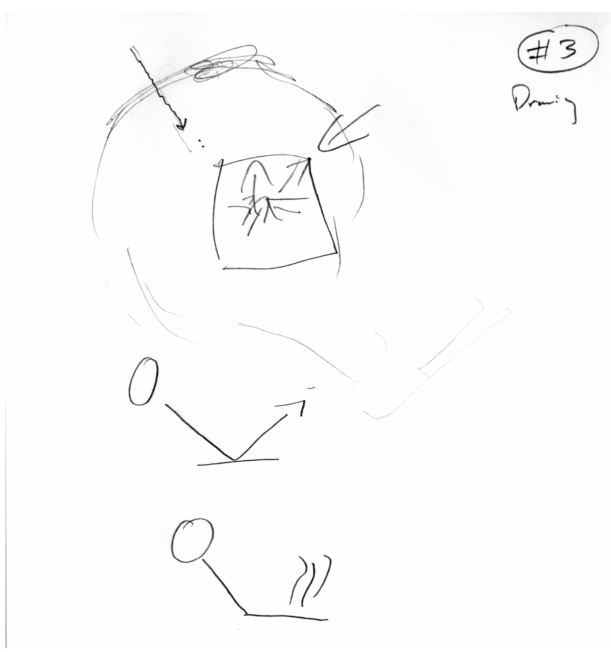
> Ozone depletion . . . is like the CFC's or whatever, like, eating the ozone layer, which allows, makes a hole, which allows more UV light to get passed through. And the greenhouse effect would be like the heating of the atmosphere, because of, like, ah, gases and stuff produced by humans. Um, and then global warming is like the increase in surface temperature and, like, ah, I would think it's caused by both of those, but I don't really know if that's true. And it, like, raises sea levels and melts glaciers and stuff like that."

When asked if the greenhouse effect and ozone depletion are different, Kevin thought that ozone depletion would be included in the greenhouse effect. However, when probed about the gases causing each, he distinguished between CFCs (including aerosol cans and Styrofoam) causing ozone depletion and carbon dioxide from cars and factories causing the greenhouse effect. Further, he did not think that the carbon dioxide affected the ozone layer. This created some cognitive dissonance because now Kevin's primary greenhouse gas was no longer affecting ozone depletion, Kevin's primary greenhouse mechanism. He started to fumble and offered the following attempts to explain how carbon dioxide influences the greenhouse effect and surface temperatures: "I don't understand if they [greenhouse gases], like, move around more, or whatever, so they cause the atmosphere to heat up more . . . or maybe just because there are more molecules in the atmosphere, they can run into each other more, which is like heating it up, but I don't really know." Soon after, he made the guess that maybe it was something about the "structure" of carbon dioxide.

In the absence of all carbon dioxide, Kevin came back to the ozone hole, suggesting that "the hole in the ozone layer could be heating up and allowing more other kinds of light to go through and heat up the surface too." But he then waffled on whether this would still be the greenhouse effect or something different. He first stated "I think I'd maybe call it the greenhouse effect, but call it global warming too." Soon thereafter he stated that the greenhouse effect and ozone depletion are different things. He next reaffirmed that the greenhouse effect is "heat given off by, or carbon dioxide given off by human activities that goes into the atmosphere and heats it up, but I don't know how it gets heated up." As we went around in circles about the three terms, Kevin eventually offered the following summary:

> "I think those three things, ozone depletion, greenhouse effect and global warming, are all like considered, they're all, like, together, but maybe they're not the exact same thing."

When asked if the media distinguishes between the three concepts, he firmly stated that they do not "because they all talk about them the same way. Because they're all bad and they all cause the same thing to the media." To the media, the things they cause are global warming and skin cancer, which to Kevin are different things. "Skin cancer is just too much ultraviolet rays on your skin and global warming is the heating up of surface temperature." At this point the interview ended.



Interview #4 with Paul on September 28 at 12PM

Paul was a freshman who had not yet declared a major at the university. Many of his science classes all the way up from middle school to high school had touched upon the greenhouse effect. However, none of these had concentrated specifically on the topic. Paul was much more confident in his science knowledge than other interviewees. He had taken two years of high school chemistry and used more developed vocabulary and science concepts in his discussion. However, as the summary below shows, Paul calls upon this science background to support several misconceptions. Paul had not talked about the greenhouse effect in any other classes yet that semester.

Paul began the interview by providing a very thorough and accurate description of the greenhouse effect, including important elements of wavelength dependent transmission of light, penetration of visible energy through the atmosphere, conversion to infrared thermal energy, and trapping of energy inside the atmosphere:

> I believe that the greenhouse effect is caused by electromagnetic radiation from something, such as the Sun, probably just only the Sun, entering our fairly thick atmosphere that, ah, the electromagnetic rays, radiation in at least one of the forms, at least of the spectrums, is able to penetrate through whatever there are, the clouds and whatever elements are in the atmosphere. And upon hitting the ground (the surface) they will be converted into heat energy, thermal energy. And, due to the, whatever, however dense, or whatever the chemical make up of the atmosphere is, the heat gets physically trapped inside. So essentially, it's electromagnetic radiation coming in, turning into heat and then being trapped in there . . . it's very similar to the way that light enters a glass greenhouse, and, ah, turns into, from electromagnetic radiation, visible, and whatever else it penetrates, into heat energy and being trapped inside. So, the result is the interior, whatever it is, being covered by the atmosphere, or the glass, is much hotter than what it would normally be.

This process occurs in greenhouses on Earth, in Earth's atmosphere, and to a large extent on Venus. He also mentioned sunlight going into a water bottle heating the water, causing evaporation, and "gross" humid conditions inside the water bottle. Paul mentioned that "if you were to leave the cap off, . . . it's colder than if you put the cap on and leave it in the Sun." The interviewer then drew a picture of a bottle of water on a blank piece of paper and asked Paul to describe the effect. Paul drew a Sun and an arrow labeled "EMR" to show electromagnetic radiation, which "penetrates through the clear plastic, assuming, of course, that it's clear." He then described that the water (and possibly the inside of any labels on the bottle) converts the electromagnetic radiation into the heat. As he drew wavy lines with arrows rising from the water, he explained that this heat is "trapped inside of the bottle. Basically, the air inside the top of the bottle and, thus, also the water, the overall net temperature is gonna rise." He explained that there is an increase in the energy overall due to the penetration of the electromagnetic radiation; he also emphasized that "instead of staying electromagnetic, the energy is going to become heat energy, thermal energy." Finally, he drew a wavy arrow coming out of the top of the bottle and explained that if the cap was removed from the bottle "it gives it an outlet so all the heat will escape and it will reach equilibrium with the outside environment."

The interview then turned to the Items 1-14 found on GECI.vB1. For the first question, Paul selected infrared and visible as the main forms of energy given off by the Sun. He had never actually dealt with ratios of energy coming off the Sun, but thought that the Sun must give off infrared "because the Sun is a really hot object." He also knew that the Sun gives off a lot of energy due to fusion. He was "not sure which is emitted by fusion, but definitely a lot of visible, since it, like most other stars, the visible will reach, you know, very, very far distances." He was also pretty sure that the Sun gives off "a lot of gamma rays because we can see very, very far with gamma ray telescopes." Note that Paul's reasoning for visible and gamma ray light has to do with the ability for these forms of radiation to travel long distances through space.

For Item 2, Paul decided that the two most abundant greenhouse gases are nitrogen and oxygen. He referenced pie charts he had seen showing that nitrogen and oxygen are the most abundant gases and then questioned, "I think, I'm guessing that those are all considered greenhouse gases, so I'm going to have to say C, nitrogen and oxygen."

The next part of the interview revealed interesting insights into Paul's thinking about different forms of energy. For Item 3, he selected that the surface is heated mainly by infrared and visible light. He knew that the ozone layer blocks smaller wavelength, higher energy light, including ultraviolet, x-ray, and gamma ray energy. He guessed that the longer wavelength energy was "not blocked as efficiently by the ozone layer" as the shorter wavelengths. With regards to radio waves, he described:

> I think they're not as strong once they reach the Earth, probably because we are 93 million miles away, and, ah, they are a lower energy, so, they possible could die out. Or maybe since they are . . . so low energy, they are absorbed more by the atmosphere. But I think, I think that infrared and visible are high enough energy so that they make it, but low enough so that they're not absorbed by the by O3, ozone.

It is not entirely clear whether the lower energy radio waves die out as they travel through space or when they are absorbed by the atmosphere, but there is definitely a sense in Paul's description that the ozone layer serves as a low-pass filter blocking out high energy light and the atmosphere underneath acts as a high-pass filter blocking out low energy light. Paul describes that visible light can pass through both. When posed with the hypothetical scenario that Earth had no ozone layer, Paul stated that "gamma rays and x-rays would . . . do most of the heating because they're the highest energy."

For Item 4, regarding the amount of energy leaving from the Earth system, Paul used sophisticated ideas of equilibrium and conservation of energy to deduce that this is equal to the amount of energy arriving from space:

> I'm stuck between less than and equal to. I know it's probably not greater, but just the concept of equilibrium makes me want to say it's equal. However, all the things we do, everything that's mechanical energy just comes from, comes from the, ah, ah, electromagnetic into heat or into photosynthesis. Ah, it, it seems like there would be a lot, a lot more energy transfer going on on the Earth, but, not necessarily leaving, I guess. Well, we probably do emit a lot of, ah, emit some, a significant amount of heat back into space, probably, just so it gets, absorbed into objects, atmosphere, potential energy of things, so, I'm gonna have to go with the equilibrium idea and say that it's equal.

By equilibrium, Paul referred to the "fact that the universe is a closed . . . environment" and that "the Earth in and of itself is also a closed environment so whatever comes in must also go out. It's gotta be, and that change should, theoretically be zero."

Item 5 asks about the type of energy absorbed by and heating Earth's atmosphere. Paul asked for a clarification of whether that included the ozone layer. The interview explained that the atmosphere included everything above the surface. Paul wanted to choose gamma rays as the main form of energy heating the atmosphere but settled for x-rays. "You mostly [hear] things like if the ozone wasn't there, then we'd all turn into bacon because of the gamma rays. But the x-rays can be very damaging. Um, they do have a lot of energy, I guess. . . . since they have the highest amount of energy, then I'd have to say, of all those choices, x-rays."

For Item 6, Paul chose that operation of nuclear power plants does not increase the amount of greenhouse gases in the atmosphere. This was based upon both a process of elimination and a perception that steam is not a greenhouse gas. He knew that nuclear power plants release steam from water and he did not view steam as a greenhouse gas. All of the other listed processes released greenhouse gases. Paul specifically identified carbon dioxide (given off by fossil fuel burning), oxygen (given off by agricultural activities), and unnamed gases (given off by fertilizers) as all being greenhouse gases. He also noted that burning rain forests would reduce the amount of one greenhouse gas (oxygen) but increase the amount of another (carbon dioxide). The interviewer paused at this point to clarify what Paul meant by steam. By steam, Paul was actually describing a mushroom shaped plume of white rising from a pot of water on a boiling stove. When questioned, he was unsure if steam was a gas. As he described it, steam seemed:

> [a] little too solid, . . . a little bit too tangible . . . too coarse. . . . I've not observed steam taking on the characteristics of a gas. . . . it behaves more like a fluid in that you can alter it's shape much more like a fluid than you could with a regular gas. It reacts to changes in shape much, much slower than any gas that I've ever been aware of. Ah, so it seems sort of on the border. But on the other side, I'm not sure exactly. Once you heat that up more, I'm not sure if it actually changes or if it just remains as steam indefinitely.

Most importantly for this study, he did not think of steam as being a greenhouse gas. He thought of it as being something more tangible or substantive.

When Paul turned the page to Item 7, he mentioned that the question altered his definition of a greenhouse gas. He recalled hearing "in the news that greenhouse gases are eating the ozone or destroying the ozone or chemically reacting with the ozone to form non-ozone substances." He was swayed by this distracter and selected Option A as his choice, stating, "For A, destroying the ozone layer, would definitely allow more high energy radiation levels to enter the atmosphere and thus it would alter the Earth's temperature, heating up, heating it. So A, then." Paul also discussed the other four choices. He acknowledged that changes to how quickly plants carry out photosynthesis could be a possible choice but thought that this would only be a very long term effect and also would not change significantly. He thought that concentrating smog and pollutants over cities could lead to local heating but would not alter Earth's overall surface temperature. This "could create a sort of greenhouse effect within the city or within the small region. But overall we're talking about the overall surface temperature. It isn't going to affect it." For the selection of magnifying and focusing sunlight, he stated:

> the atmosphere as a whole, I think, does that. It changes the light direction slightly, which is why you get the larger moon when it's just rising and setting sometimes. It's not gonna magnify or focus it to the extent that it's actually gonna change the temperature, I don't think, because the fact that it's greenhouse gases aren't gonna change the magnifying and focusing characteristics of the atmosphere. I think it's gonna do that regardless of what gas it has.

Paul selected Option E, that greenhouse gases influence the flow of energy through the atmosphere, as the second best choice after ozone depletion. "Energy travels differently through different, ah, heat'll, heat, heat will flow differently through different substances and gases just 'cause of their specific heat and then their other characteristics, but I think that's definitely a lesser effect than eating, eating holes in the ozone layer and letting large amounts of radiation in. So, I think heat does affect it, but not nearly as much as choice A does." Ranking his choices, he chose A (ozone depletion) first, followed by E (affecting flow of energy), and lastly C (smog and pollutants) but only at the local level.

Item 8 and 9 asked the types of energy reflected and radiated from Earth's surface during the daytime. During this discussion, Paul first described that it definitely reflects visible light because you can see the Earth. He also referenced our ability to see other planets and the visible light reflected by those planets. With regard to other choices, he stated "it [the Earth] is not emitting very much, relatively, as far as infrared, just 'cause it isn't a terribly warm planet relative to things like stars and, also, I think, ah, [infrared] tends to get sort of lost or absorbed more. Ultraviolet and x-ray, they don't make it into the Earth's atmosphere, or to the surface so much. And radio, I think that again, it's a lower energy, so it's not gonna make it quite as far." Within this statement is the sense that the lower energy forms of light are somehow more prone to disappearing or fading away.

For Item 9, Paul initially responded that the surface mostly gives off visible light. However, he quickly asked for clarification of the phrase "gives off" and wanted to know if this was a general term for things leaving the surface or actually originating on the Earth. This question was re-directed to him, and he reasoned that the Item 8 term "bouncing" referred to things that "originated from the Sun" while "gives off" referred to things that originated on Earth, either through "humans, human creations, or heat, infrared radiation given off from the heat of living objects from the planet's core and mantle." He provided examples for the radiation of the lower energy forms of light listed – radio waves from radio broadcasts, visible light from street lights that convert electrical energy, visible light from fires that convert chemical energy to heat energy, visible and infrared light from lightning, and infrared light from "living things that generate heat . . . that will give off the infrared radiation." He also mentioned infrared light generated in the planet's core, but described that "they're probably stopped pretty well by the time they reach the surface, so it's contained." He could not think of any significant processes (other than "military experiments") that would give off ultraviolet or x-ray energy. After going through this list of examples, he then changed his answer to Item 9 to infrared because there's "so much life on Earth, so many things that generate heat."

Interestingly, Paul never referred to heat given off by the surface due to absorption of energy from the Sun.

The same logic was used for Item 10 which involves energy given off during the nighttime. Paul thought that infrared light would still be the primary answer because all of the processes he had listed above would "remain pretty constant, whether it's day or night, maybe even a little bit more because people are gonna start lighting fires, [and] turn on more lamps that are gonna give off some infrared, as well as visible."

Item 11 allowed Paul to reiterate his model for the greenhouse effect, which involves both trapping of energy and an increase in the amount of sunlight coming in through the ozone layer. He chose the correct Option B, stating:

> ever since the Earth has had an atmosphere, the greenhouse effect has taken place, 'cause you have the two things that you need—the atmosphere and the incoming radiation from the surface for which the radiation bounces off. Recent human activity has, I believe, enhanced it because we're allowing more radiation to enter and . . . we haven't significantly changed the amount that is trapped in or the amount that's allowed to escape. So if you keep the same retention and you increase the amount of energy that's going into it, then overall it's gonna increase the effect.

Paul identified the burning of fossil fuels as the primary recent human activity that was enhancing the greenhouse effect and that these were "chemically changing the ozone layer . . . disabling the ozone layer . . . from absorbing certain types of radiation that are more . . . short wavelength." He referred back to his the drawing of the bottle to explain the effects of recent human activity. "Instead of having a barrier where you can sort of see through it or you can see sort of fuzzy things through it, you can see exactly right through, right where it is, so, ah, more, more radiation is not being absorbed and is actually reaching the surface."

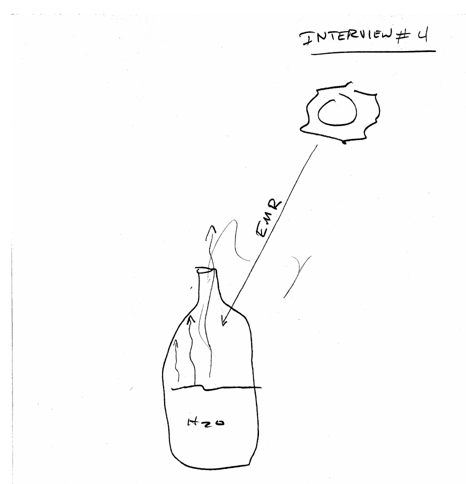
The interview then turned to the diagram in Item 12. The interviewer described the difference between solid and dashed arrows. Paul chose Option D, noting that the diagram "definitely [had] all of the aspects there with the reflecting off the surface and being trapped inside, but also some of it escaping." When asked if the amount of energy leaving to space (the dashed arrow) was the same as the amount of energy arriving from space (solid arrow), he thought that there was probably less energy leaving. However, he knew from his previous response to Item 4 that the system had to be in balance, so he guessed that maybe the diagram didn't show all the forms of energy involved. In addition, there was perhaps "energy in different forms leaving, not necessarily radiation."

Paul responded to Item 13 with a certain amount of surprise and uncertainty. He stated hesitantly "As far as I know, the Earth's atmosphere does not actually radiate anything . . . I have never heard of the atmosphere actually emitting anything." He thought that the atmosphere absorbs things that can "force chemical reactions" and that these chemical reactions might produce radiation, but he restates, "I've never, I've never, ah, learned of the atmosphere emitting anything." Paul asked if there was an option for "none of the above."

For the last question of the survey, Paul introduced a new concept that greenhouse effect moderates extreme temperatures. He described that Mercury, which does not have a greenhouse effect, has more prominent daytime (+200 degrees) and nighttime (-200 degrees) temperature extremes. He also mentioned that even though Earth is farther from the Sun than Mercury, its average temperature is comparable to Mercury's average temperature. He used this logic to infer that the greenhouse effect makes Earth warmer. He chose Option A because he did not "think that it can be permanently trapped. I think that's pretty impossible." In Paul's mind, nothing is permanent and the atmosphere could change due to human activities, impact events, or any number of other possibilities.

The final phase of the interview asked Paul to clarify his descriptions of thermal energy. He provided an explanation of "thermal energy" that is more characteristic of the scientific definition of "temperature." He described that thermal energy as a "form of kinetic energy." He described heat as a "measurement of the energy that is contained by the atoms or molecules vibrating" and referred to molecules of steam as being "more free flowing" and vibrating faster than molecules of ice. "Because it has movement, it's gotta be a measurement of the kinetic energy, but it's in different units." When asked how this heat energy flows through the atmosphere, Paul described that "thermal energy is definitely a form of energy that needs a medium, and the atmosphere is definitely a good medium. It's gaseous and so the temperature, not the temperature, but the, the heat and the thermal energy will flow between the molecules pretty freely. . . . The thing with that and the greenhouse effect is that the greenhouse effect is where the radiation hits the atmosphere, either bounces off the surface or is absorbed directly into the atmosphere, becomes thermal energy and then the thermal energy is, it's contained by the atmosphere, by the gases in the atmosphere." When asked if this thermal energy has more difficulty getting out, Paul described that the energy cannot get out as thermal energy because "the space outside of it [the Earth] is pretty close to a void and so there isn't anywhere for it to go." In Paul's model, thermal energy requires a medium to travel through. When asked how energy leaves the Earth system, Paul explained that electromagnetic radiation "does not require a medium."

Unfortunately, at this point the tape recording ended, even though the conversation continued for another 2-3 minutes. The interviewer recalls that Paul's follow-up comments indicated that he thought thermal energy was different from or disconnected from electromagnetic radiation. Even though he had referred several times to hot things giving off infrared energy earlier in the interview, he did not connect infrared radiation as a way to transmit thermal energy. He repeated that thermal energy needs a medium to be transmitted and implied that thermal energy must be converted to electromagnetic energy before it could escape the Earth system.



Interview #5 with Conan on September 28, 2005 at 1:15PM

Conan was in his third year of college and had circled junior on the survey, even though he thought he was probably considered a sophomore by the university because he had transferred. He was an arts major, but he used to be an engineering major and had circled "other" for his major on the survey. In either high school or middle school, he had covered the greenhouse effect and global warming for maybe three days, but not in any depth. Currently, Conan was enrolled in two classes that covered the greenhouse effect. One was the planetary science class from which he had been recruited for the interview. The second was an introductory atmospheric science class for non-science majors. This second class had already covered certain aspects of the greenhouse effect between the time of the initial survey and the interview. Conan made periodic reference to the instructor for this class, whom has been given the pseudonym of Dr. Sullivan.

When asked to describe the greenhouse effect at the outset of the interview, Conan explained that he had learned in Dr. Sullivan's class that "the atmosphere holds in the heat from the Sun" and that the release of gases, from things like burning coal and carburetors of cars, "forms a layer of a different kind of gas inside the atmosphere, or a high concentration of it, and so the heat can't escape as much from the atmosphere as it should." He had also learned in class that "there's supposed to be an equal release of energy as there is to an increase in energy, so it's supposed to be a balance, and the lack of balance causes then more energy inside the system of the Earth, and, therefore, the energy converts to heat." When asked about where this converted heat goes, he assumed that it bounces back and forth between the clouds and the Earth. When asked if the greenhouse effect was a recent or old phenomenon, he referenced a recent television program about "global warming" and indicated his belief that it has "been around for a while, it's just that it's to a higher level recently, so it's affecting the Earth more than it did." He then mentioned possible connections between this and hurricanes. When questioned about the difference between the greenhouse effect and global warming, he explained that "the greenhouse effect is how the gases, I mean, how the heat is held inside the Earth and it's supposed to be there. And then global warming is when it goes to an extent which, um, not as much energy is being released as gained, so, um, . . . global warming is the melting of the ice caps, the increase in heat in the oceans and, ah, just, I don't know if I'm even using this term right, latent heat, I guess, stuck on the Earth."

After this initial introduction, the interview turned to Questions 21 through 34 of GECI.vB2. For Item 21, he debated between visible and infrared light as the main energy source from the Sun. "I know visible is what we see, and there's a lot of visible light, but there could be more infrared because I can't see it." He eventually went with visible light as his answer because it was the only form of light he could personally measure. He also mentioned that he knew it was not ultraviolet because "if there was a lot of ultraviolet, we'd probably all be dead."

On Item 23, Conan selected ultraviolet light passing through the ozone layer as the main source of heat at Earth's surface. As described above, he knew that infrared does heat the Earth, but he was not sure how much. He knew that "ultraviolet stuff that does pass through the ozone layer is the problem with global warming, or supposedly," and used this to infer that even if there wasn't an ozone problem that some ultraviolet energy "would have to affect the environment in some way." He did not select infrared because he didn't think it was as important as ultraviolet energy.

Conan's response to Item 24 below provides a good example of student difficulty with survey options involving a mix and match of answers. He initially selected Option B – energy out of the Earth system – but after reading the question more closely realized that Option C was also relevant. It then took nearly a minute for Conan to arrive at his final answer of Option E:

> Yeah, I think I would, B and C, if I'd read it properly. I just kinda overlooked it. I just assumed that, you know, that A and C are, it was gonna be like A and C, or, um, B and C. Oh, wait, no, I mean A and C. So I just assumed it was A and C. Wait. Lemme look at this again. (laughter) I thought it was gonna be A and C and A and B. There we go. So, I, I automatically cut out A, so I just assumed that, yeah . . . My final answer is, ah, B and C, so E.

Item's 25 and 26 distinguish between energy absorbed in the upper and lower atmosphere. Conan thought that the upper atmosphere was mostly heated by x-rays because he assumed that the other wavelengths (visible, infrared, and at least a little bit of ultraviolet) got through and because x-rays are "really damaging . . . the scientists that studied them got cancer." Conan justified the fact that lots of x-rays were not coming through the atmosphere and damaging life on the planet by assuming that they were being absorbed by the upper atmosphere. He also guessed the lower atmosphere was heated by "ultraviolet and the greenhouse section of it" and indicated that he thought the greenhouse effect occurred only in the lower part of the atmosphere. He did not think that greenhouse gases were present in the upper atmosphere because the "atmosphere thins as it gets higher."

For Item 22, Conan originally selected oxygen because he knew that oxygen and nitrogen are the most abundant gases in the atmosphere. He did not change his answer after the interviewer clarified that the question was asking about the most abundant greenhouse gas. However, when he got to Item 27 which asked which gas was not a greenhouse gas, he had an insight that made him change both answers. He had originally wanted to select water vapor for Item 27, but after explaining that water vapor was lower in the atmosphere and important for maintaining regular temperatures and helping disbursement of heat, he decided that water vapor probably was a greenhouse gas "seeing how I just described, like, the process that sounds like the greenhouse." He then eliminated ozone, methane, and carbon dioxide as well as water vapor for Item 27 (because he thought they "made more sense" as greenhouse gases) and chose oxygen as the correct answer. Recognizing that oxygen couldn't be both the most abundant greenhouse gas and not a greenhouse gas, he asked if he could change his previous answer for Item 22 to water vapor. He now recognized that nitrogen and oxygen were the most abundant gases, but that water vapor was the most abundant greenhouse gas.

As part of the preceding discussion, Conan also mentioned that he thought "ozone is part of the greenhouse effect, since they always consider the ozone layer and assume there's a hole in it." The interviewer followed up on this and asked who he was referring to with the word “they.” He identified “specialist teachers . . . people in common conversation, [and] peers.” He also offered a rather interesting general statement about education:

> I guess that's just everything I've heard or maybe inferred over time. For the same reason you touch a stove and you know it's hot when it's on. That, that's just what I think I've, I've gained, but it may be wrong, but it's so imbedded in me that I just accept it as part of it.

The other selections besides oxygen made “more sense” as greenhouse gases because he had heard more about these in greenhouse discussions, and he had heard the least about oxygen.

Jumping ahead for a moment to the end of the interview, it is important to note that Conan repeated this same justification for his response to Item 34. He thought that greenhouse gases interacted most strongly with ultraviolet light. “I've always heard that ultraviolet's the problem from, again, they, the people that tell me, um, the teachers, peers, the news, whatever specialist comes on and says ultraviolet is the problem. It just seems, like, ingrained in my skull.”

Returning to Item 28 regarding mechanisms for the greenhouse effect, Conan selected more sunlight passing through the ozone hole as:

> [the most likely] source of temperature changes, because more sunlight passing through the ozone hole, the extra sunlight, basically would cause there to be more heat in the Earth and then not as much, I mean the same wouldn't be escaping or less because of the release of whatever gases that were being released by industry and such.

He did not like the air pollution answer because it sounded backwards that air pollution would be trapped rather than being responsible for the trapping of heat. He thought the rising of gas molecules would cool the planet rather than heating it. He did not thing there was enough heat coming from factories and industry to contribute significantly compared to energy from the Sun. Finally, the correct answer (energy being absorbed and given off by gases) sounded like a distracter, “like something written to sound right.”

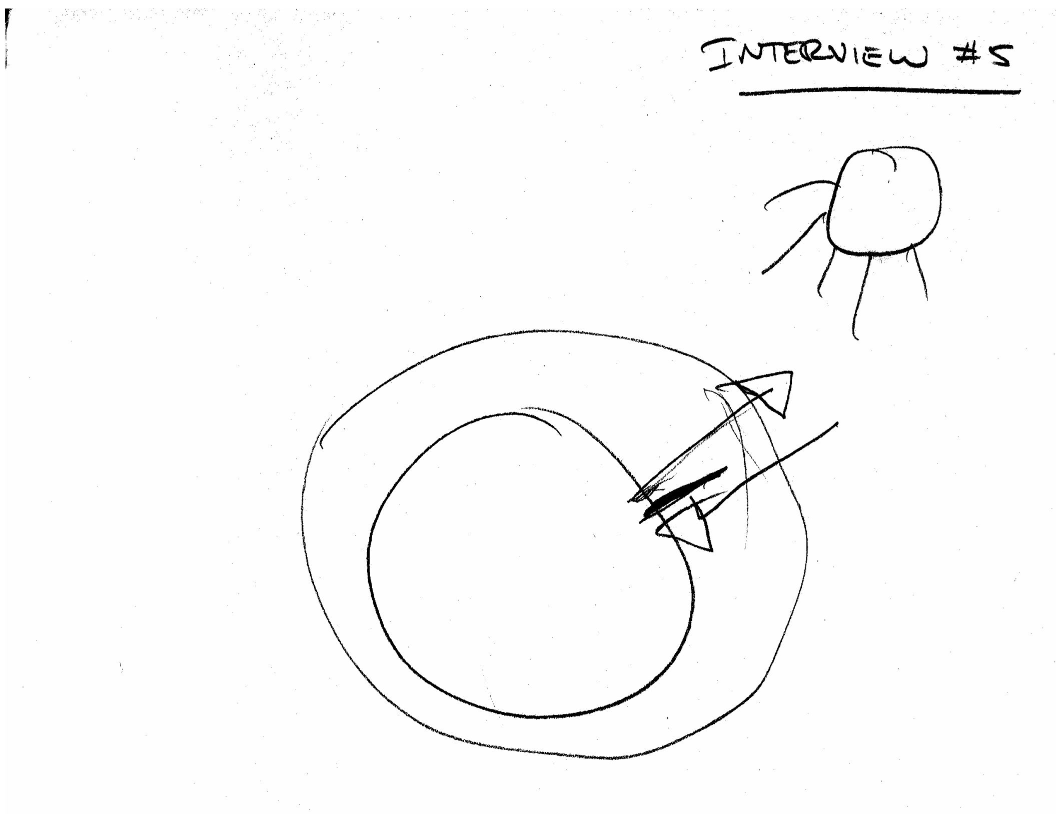
The interviewer probed Conan more regarding air pollution. He identified excess CO_2 out of balance with the carbon cycle as one form of pollution: “it’s basically an excess of gases that we already have that aren't being put through a cycle . . . the CO_2 that's released [from burning and other natural processes] is supposed to go through a cycle and then it returns in the form of carbon . . . and then it can be burned again. Otherwise . . . we would just be continuously going towards, like, global warming and that kind of problem if there wasn't some sort of process to deter it. And the problem today is that there's more going out, I think there's more CO_2 going up into the atmosphere than there is carbon returning to the Earth." He also identified sulfur (of some type, maybe sulfuric acid) and particles that help form smog as being forms of air pollution. However he did not think that smog would contribute to the greenhouse effect, because if anything "black smog and stuff would probably keep some of the heat from hitting the surface of the Earth and if the whole world was covered with smog, I would assume that it would be a lot colder on the Earth 'cause there isn't as much sunlight coming down. Because, a lot of what comes down is, I am assuming, is visible light, and so visible light produces some heat, and there's so much of it that it produces a lot of heat overall." This statement highlights two important points: 1) Conan has constructed a model in which particulate smog is not a part of the greenhouse effect, and 2) Conan identifies visible light as heating the Earth, although on previous questions (Items 23, 25, and 26) he had identified x-rays and ultraviolet light as the major heat sources.

For Item 29 dealing with reflection of light, Conan initially selected radio waves as the most likely answer because radio waves seemed more wavelike than other forms of electromagnetic waves (even though he knew these were also part of the electromagnetic spectrum). Because the answer was asking about reflection, he thought that the most wavelike energy would be most likely to reflect. When asked what his answer would be if the word "most" was removed, he at first selected visible, ultraviolet, and radio. When asked why he hadn't picked x-ray, he based his answer on x-ray machines and stated, "you kind of imagine in your head the x-ray waves going through the planet and not really bouncing back as much." However, he eventually selected all of the forms of energy as being able to reflect. To get to this point, he accepted that all of the choices were waves and that "waves have to bounce off something." The interviewer then returned to the initial question and re-inserted the word "most." Conan now chose infrared and visible as the most likely to be reflected, explaining that these had longer wavelengths than radio, ultraviolet, and x-ray energy. The interviewer clarified that Conan thought radio waves had shorter wavelengths than visible and infrared. Conan also expressed the idea that shorter waves (in particular ultraviolet and x-rays) were more likely to penetrate skin and cause cancer. Longer wavelength energy (infrared and visible in Conan's mind) could not penetrate skin and were therefore more likely to reflect off of, rather than penetrate, the surface of Earth.

For Item 30 regarding energy given off by Earth, Conan explained that infrared light the best choice, stating "None of the others seem close to right." The interview quickly moved on to Item 31, where Conan explained that the greenhouse effect was most effective "during the latter half of the day and the early part of the night." However, this was not one of the options for the questions, so Conan selected Option E – all the time.

In agreement with his previous statements about pollution and the carbon cycle, Conan thought that the greenhouse gases occurred naturally in the atmosphere on Item 32. He described brush fires caused by lightning as an example of a natural occurrence that would release CO_2 into the atmosphere. And for Item 34, he selected Option A that the greenhouse effect is a process that has operated for most of Earth's history, because this was the only option that did not have the word "recent." Conan explained, "Because it's not a recent thing. I already established to myself that it has always existed, but just exists at a different extent today." Additionally, the other non-recent option (Option B regarding plants and humidity) seemed like it was "talking about something else" and seemed "too specific."

To wrap up the interview, Conan was asked if he distinguished between ozone depletion, the greenhouse effect, and global warming. He stated confidently, "My understanding was that greenhouse effect exists, and because of the depletion of the ozone layer, more ultraviolet light gets in, which increases the heat and the greenhouse effect holds in that heat, and then, thus, causes global warming." When asked if ozone depletion is part of or different from the greenhouse effect, he paused but then explained, “I know the ozone is a thin layer around the Earth and it's part of the atmosphere and, to my understanding, it is part of the greenhouse effect. Um, yes, yes, yeah.” At this point the interview ended.



Interview #6 with George on September 28, 2005 at 3:40PM

George was a junior at the university. Although he had originally been a business major and had recently changed to economics, he had circled "undeclared" on the survey when he completed it at the beginning of the semester. In high school, he had briefly touched on the greenhouse effect but never extensively. In addition to the class from which he had been recruited, he was taking a class that semester about the history of the southwest environment that had mentioned that the greenhouse effect was heating up the air; however, this class had not discussed the causes of this heating.

At the beginning of the interview, George provided his definition of the greenhouse effect:

> My understanding of the greenhouse effect, it's from fossil fuels from such things as cars, industrial, just anything that's not really natural, just burning of such things. And, these, ah, I guess, emissions around the atmosphere and, they don't let as much energy as leave the atmosphere, as it would if they weren't there which makes the Earth hotter, because it traps in the energy from the Sun, rather than letting it out. So, it heats up things like the ocean and causes weather, the climate, and all kinds of things to happen.

George initially explained that "excess CO_2" or "chemicals coming out of the burning of fossil fuels and stuff from industries like cars and stuff" were responsible for doing the trapping. After discussing that these gases "spread out in the atmosphere," he interrupted the next question stating, "Oh, wait, wait, and, I just know this from a TV show. I guess it's, like, O_3." He explained that something was "way up there" that was "not necessarily breaking up the O_3 molecules, but it takes a certain other chemical to make O_3 molecule, and they're hurting those things. It's not always polluting the air, but it's destroying it." He then mentioned "there's a hole in the ozone layer" and that "the good chemicals are getting destroyed . . . by the bad ones." The interviewer continued probing about the energy he had mentioned earlier. George thought this energy came from the Sun (in the form of solar radiation) and got trapped in the atmosphere. He thought that "45% of the Sun's rays actually reach the ground, 'cause it's deflected through the atmosphere and all that stuff. And then the ground itself reflects the rays back towards, or just out in space, and because the excess, these excess bad chemicals, I guess, [whatever] you want to call 'em, they reflect back down to Earth, so then you have another, more energy coming, but would then deflect from the ground comin' back towards Earth, so that's where the excess energy is coming from." He drew a picture showing this energy flow and emphasized that energy is "reflected from the ground back into the air and back to the ground."

George had completed survey GECI.vB1, so the interview turned at this point to Item 1 on the survey. He did not think the Sun gives off much radio or x-ray energy. He assumed the correct answer was either Option C or D because the "Sun gives off lots of visible light you see with your eyes." He guessed that the other energy besides visible was ultraviolet.

For Item 2, George was at first confused by the question. He knew that "the greenhouse effect is what is considered bad" but though that "maybe greenhouse gases are what actually are the good ones in the atmosphere." After the interviewer clarified that greenhouse gases are the gases that cause the greenhouse effect, he stated "I know CO_2 is really bad" and selected CO_2 and methane as the best answer. When asked why he hadn't selected other options listing CO_2 with ozone and CO_2 with water vapor, George used a bad-good philosophy. "I know ozone, O_3, that's good . . . and water vapor, that's not bad. I mean that's just clouds and stuff, I mean, there's water vapor everywhere." When asked more about CO_2, George stated "I just know that it's bad. I don't know why it's bad, but I know it's bad." He had learned this "through the grapevine" which included TV shows, articles in the paper, classroom conversations, and such. Interestingly, he mentioned that he had not talked much about the topic with his friends. Jumping ahead to George's answer to Item 6 of the survey, he reused the concept that the greenhouse effect is bad for the environment when deciding which activities produced greenhouse gases. Each of the other activities listed involved activities that were 'no good" or "probably doesn't help [the atmosphere]." When questioned about nuclear power plants as a choice, he recognized that nuclear is fairly clean and that water for cooling the uranium core was not the problem. However, he mentioned radiation and public fears of radiation: “People are always saying ‘Ah, nuclear!’ . . . It’s not acceptable, I’m guessing . . . I’m sure the radiation and whatnot that comes from it doesn’t help.” He couldn’t see why growing rice and raising cattle would be bad for the atmosphere and selected this choice.

George thought the Earth was mostly heated by infrared and ultraviolet for Item 3. He eliminated visible light as an option because he thought “visible is more reflective. That’s why it’s visible, because it reflects off things and goes into your eyes.” He explained that ultraviolet rays cause cancer so they were more likely to “heat up things.” He also mentioned that he had seen a demonstration of infrared light in class and learned that infrared is “actual heat going through the air, so probably that’s what’s going to heat things up is heat.” He expressed a clear model that things that reflect energy do not heat up and used this to eliminate visible light, because it was mostly reflected.

George’s answer to Item 4 involved similar logic. He thought that the energy leaving Earth to space was equal to the energy arriving, but he originally based his answer upon average temperatures: “during the day, it [Earth] takes in energy and at night it gives it off” and “summer days take in more energy, but . . . winter gives off more energy, . . . so I think on average they’re the same.” When asked if the Earth gives off heat during the day, his response was “Sure. Why not? Actually. Let me, let me think about this for a second.” The conversation went back and forth on this topic, but George eventually described that the Earth surface is “constantly heating up, but it doesn't actually give off heat during the daytime. The only thing it gives off is reflected stuff that you feel as heat, but it's not actually heat from the Earth. It's just heat from the radiation reflecting.” He was not positive but agreed that this was closest to how he thought about it.

He later changed his mind about this concept when answering Items 8 through 10. He selected visible light as being mostly reflected by Earth during the day, infrared as being given off during the day, and ultraviolet as being given off during the night. He also used the fact that Item 9 implied that the surface gives off energy during the day to decide he had been wrong that in his explanation above. He suggested that asphalt is hot during the day and offered, " I'm going back and I'm changing my mind about the energy during the day thing." He also provided interesting logic regarding why he had selected ultraviolet for the nighttime. On television, he had seen images from helicopters using infrared cameras at night. Because the surface looked black in these images, he figured there was "not a lot [of infrared], or else the camera would pick it up."

Similar to his answer for Item 3, George tried to decide between infrared and ultraviolet as the main agent for heating the atmosphere on Item 5. He guessed ultraviolet because it "has really, really small wavelengths and I'm thinkin' they can just go around the atmosphere." The interviewer asked George to draw what he meant. George drew a diagram on the top left of the page showing several dots to represent molecules and a wave-train of very short wavelength passing through without hitting any of the molecules. He also drew more molecules below and to the right of this and explained that "Infrared is a little bigger so it hits 'em." He drew a larger wavelength wave-train coming in from the right and hitting an atmosphere molecule. He explained that this involved "energy transfer" that changes the direction of both the molecule and the infrared energy. He drew arrows going in opposite directions after the collision, one to represent the molecule and other to represent the energy. The result of this collision is to "heat things up. [It] shakes it up a little bit."

For Item 7, George selected Option E and explained that the answer was consistent with his model that the greenhouse effect "traps in the energy, and how it lets more in and also it traps excess energy back into." He thought that Option A regarding the ozone layer and Option D regarding magnification of light were both consistent with Option E, making it the most attractive choice.

George had difficulty selecting a choice for Item 11 regarding the greenhouse effect and humans impact on it. He knew that Earth's climate has been changing over Earth's history, but he also linked the term greenhouse effect with climate change – "most people consider the greenhouse effect to be caused by humans burning excess fossil fuels." He knew that the last three options regarding humans either not influencing or actually decreasing the greenhouse effect were wrong. But he had trouble with the other two choices. He finally chose Option B, describing that climate change has been going on for Earth's history and humans are enhancing climate change. Interestingly, he was not thinking of the greenhouse effect as a natural process that increases temperatures above the effective temperature. Rather, he was considering the greenhouse effect as climate change due to increases in carbon dioxide, which he thought could be natural or due to humans.

For Item 12, George selected Option D, the proper diagram showing heat flow through the Earth's atmosphere. He knew that Earth's surface gave off heat, so Option A was definitely wrong. He described a very clear understanding of the concept of radiative equilibrium when explaining why Options B and C were incorrect; in these diagrams, "none of it is ever released back into the atmosphere or leaves the atmosphere. And that's impossible 'cause the Earth would get so hot and it'd just melt and blow up or whatever. It has to give off some energy."

George also had trouble with Item 13 regarding the type of energy given off by Earth's atmosphere. He decided it was definitely not radio or x-ray: "Radio waves, they have no friends, they're just off in their own little world. They're big, long things that, no one cares about 'em. And x-ray, you don't ever hear about x-ray being talked about unless you broke your bone or something." He also eliminated visible because the surface is "reflecting it. It's not giving it off." He admitted to totally guessing between ultraviolet and infrared and ultimately selected infrared.

When confronting Item 14, George first expressed his belief that the greenhouse effect may not be responsible for climate change. He thought the question was tricky "because like I was saying earlier, the climate of the Earth has always been changing and there's always been in fluctuations and you don't know if it's going to go cooler next year, you just don't know. So there's absolutely no evidence, that it's due to the greenhouse effect." If he had to choose an answer besides "other," he chose Option A, that the surface is warm due to temporary trapping. He selected this over Option B "because energy is not permanently trapped in the atmosphere. I mean, it stays in for longer than it usually should, but eventually, it goes away." The interview returned to the diagrams on

Item 13 and George confirmed that his answer of Option D was consistent with the idea of temporary trapping because some of the energy got out. He also recognized that Options A, B, and C represented permanent trapping."

After completing the survey items, the interviewer asked George to provide some everyday examples of infrared and ultraviolet light, the two forms of energy George had been having trouble distinguishing between during the interview. After some initial denial that he could give any examples, he offered that "infrared is heat coming off of, like, right now you're giving off infrared light, I just can't see it." For ultraviolet, he described, "For some reason I always think of, like, pink and stuff like that, and purple as ultraviolet."

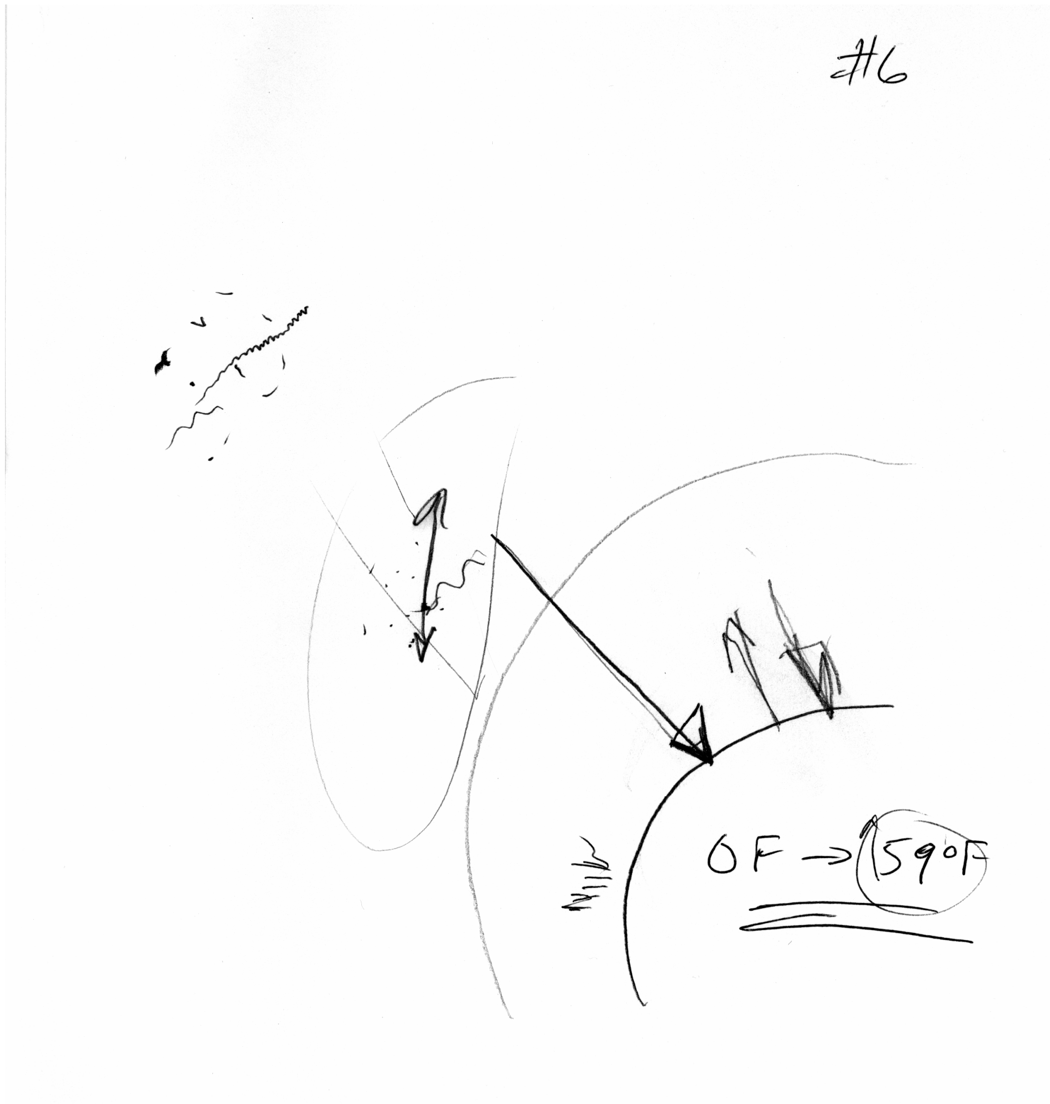
George was then asked to describe the difference between ozone depletion, the greenhouse effect, global warming, and air pollution. He drew a picture of the Earth and a layer above the Earth. He described ozone as a "haziness around" the Earth. He explained that "ozone helps protect us from the Sun's radiation. It helps keep the Earth more cool; it helps to just protect us in general from, like, skin cancer and stuff like that." He next explained that the greenhouse effect is caused by air pollution and that that the greenhouse effect is the same as global warming. Air pollution is "what is made from cars and factories and burning of too much anything."

Finally, George summarized the greenhouse effect one last time. He explained that the greenhouse effect is "due to air pollution" and that:

> there's excess CO_2, and other chemicals or molecules, whatever you want to call 'em, in the atmosphere, which disturb the energy flow from the Sun . . . So you got your Earth here, and you got your atmosphere. So you got like the picture, in the exam, the Sun coming in and as it's coming in, not all of it reaches the Earth, but due to the air pollution, the actual atmosphere that helps reflect the Sun is being diminished, so more radiation from the Sun is actually reaching the Earth which causes it to warm up and not even that, the energy possibly leaving gets trapped in, so not only is there more energy coming in, but not as much is leaving, so it's being temporarily held in.

He described that the energy is being released by the surface and reflected back down by the atmosphere. Finally, he re-emphasized that the energy is being "temporarily trapped.

There's energy leaving and going out all the time." In this final description, George has called upon several of the ideas that he confronted while going through the survey to add to his description of the greenhouse effect. At this point, the interview was ended.



Interview #7 with Raoul on September 29 at 5:30PM

Raoul was a sophomore at the university. He had not yet declared a major but was inclined towards international studies or political science. He had taken a high school class and an astronomy class during the previous semester at the university that both briefly touched upon the topic of the greenhouse effect. Finally, he was not enrolled in any other classes during the semester of the interview that had covered the greenhouse effect.

As with most of the other interviews, Raoul was first asked to provide his own description of the greenhouse effect. Raoul explained:

> The greenhouse effect. All right. Ah, physically I would say I think it's that, um, more energy gets trapped in the Earth's atmosphere, the Earth obviously receives most of its energy, pretty much all of it, from the Sun. Ah, the greenhouse effect would be it can radiate away less of that than it receives, or I guess it would always radiates away less than it receives . . . making the planet hotter as a whole.

He invoked a "law of physics" that "nothing is a perfect absorber of energy" to explain that "if the Earth were to absorb all the energy it received from the Sun just constantly, it'd just be immense temperatures and go just hotter than the Sun, or as hot as the Sun." However, because the Earth radiates energy away, "we get our nice ambient temperature that allows for life and all kinds of other nice things." When asked, Raoul clarified that the greenhouse effect causes the Earth to keep more energy than it normally would. Interestingly, he stated "it would still be radiating more of the energy away than it receives, but it would be keeping a greater fraction of that."

Raoul was then asked to draw a diagram showing the Earth. He added in a very thin atmosphere to a portion of the drawing. When asked to draw arrows showing the amount of energy the Earth receives and the amount it gives off, he drew arrows that were almost equal in length and then highlighted with a bracket that the outgoing arrow was slightly smaller than the incoming arrow. He decided the two arrows were probably close to equal and stated "I guess it radiates away less than it receives, but, but it's close to equal, which keeps the Earth relatively cool compared to the Sun." Raoul expressed a mental model that if the Earth radiated much less than it receives, then the Earth would be the temperature of the Sun and if it radiated away all the energy, it would be absolute zero.

Raoul had completed Survey GECI.vB1. The interview turned to a discussion of Item 1 about energy given off by the Sun. Raoul picked infrared and visible. The choice of visible was based upon the fact that humans evolved to see visible light. It must be, therefore, a prominent range of light given off by the Sun. For selecting infrared, he explained that "the choices further up, ultraviolet, x-ray, are more energetic forms of light and a hotter star would probably give off more in that spectrum, or hotter body of whatever type." Because he knew that the Sun wasn't a particularly hot star, it probably gave off more infrared. When Raoul got to Item 4 on the survey, he selected the same choices of infrared and visible heating the surface of the Earth based upon his answer to Item 1.

For the most abundant greenhouse gases (Item 2), Raoul initially selected nitrogen and oxygen, giving percentages of 70% and 30% for these gases, respectively. However, after clarifying that the question asked for the most abundant greenhouse gases, he quickly changed his answer to carbon dioxide and methane. Going through the other choices, he did not select carbon dioxide and ozone because he thought that ozone was broken down at too slow of a rate so it was not abundant. Helium was also not very common on the Earth. When he came to water vapor and carbon dioxide, he recognized that there is probably a lot of water vapor in the atmosphere because of Earth's oceans, but offered that it was not "all that significant, because it gets rained out primarily." He thought there was probably more water vapor than methane in the atmosphere but stuck with methane based on a hunch. He mentioned that methane might also be broken down by sunlight and that most of Titan's atmosphere was methane. The interviewer continued to press, asking what the right answer would be if water, CO_2, and methane were all greenhouse gases. Raoul eventually switched his answer to carbon dioxide and water vapor. He explained that he hadn't noticed water vapor when he first read the question.

Raoul gave responses to Item 4 that were consistent with his initial discussion about the Earth radiating less of the energy than it receives. When asked where the other energy goes, rather than the expected response that it stays in the atmosphere, Raoul said that "in time, it probably all eventually radiates away, but the Sun is perpetually providing energy to us." He then came back to the "perfect absorber" concept, stating that nothing can be a "perfect absorber or, I guess in this case, . . . a perfect radiator of energy."

For Item 5, Raoul stuck with visible light stating that "the bulk of our energy gets to us in visible light. I think we radiate away most of our energy in the infrared."

Item 6 involves sources of greenhouse gases. Raoul selected operation of nuclear power plants because "the operation of the nuclear power plants relies on radioactive decay and that's, ah, radioactive metals that are used, and that doesn't really have anything to do with greenhouse gases, I guess, they let off water vapor." Even though water vapor is a greenhouse gas, nuclear plants did not emit enough water vapor to really do anything.

For Item 7, Raoul selected Option E that greenhouse gases influence the flow of energy through the atmosphere. Option A regarding ozone was a good distracter, and Raoul mentioned, "I think greenhouse gases somehow have to do something with destroying the ozone layer. I'm not really sure how, but I think my understanding is that ozone layer protects us more from x-rays and more energetic flows of light that are more harmful to us. But I still think E's the better answer."

Items 8 through 10 involved energy reflecting off and radiating from Earth's surface. He properly justified his correct choices with the following explanation: "Most of the energy bouncing off, reflecting from the Earth's surface during daytime would be, would still be visible and I would say at all times of day, ah, daytime and nighttime, the Sun radiates, or the Earth radiates off more energy in infrared." He also properly answered Item 13 that the atmosphere gives off mostly infrared. He thought that the Earth (both the surface and atmosphere) radiates mostly in the infrared.

Item 9 involved the relationship between the greenhouse effect and human activity. Raoul gave a very sophisticated response:

> I think atmospheres, in general, would contribute to some sort of greenhouse effect, keeping the planet warmer than it otherwise would be if it didn't have an atmosphere. At various points of history, I think, say, like during . . . the era of the dinosaurs, I think it's speculated that carbon dioxide was in greater concentrations in the atmosphere and generally believed to be warmer back then and warm as a whole over Earth. Um, just Earth has gone through various, ah, heating and cooling periods throughout its history.

Because the above answer did not involve any human activity, the interviewer asked Raoul why he had selected Option B (that recent human activity was enhancing the greenhouse effect) over Option C (that humans have almost no influence). He described his understanding of the current status of the debate over global warming:

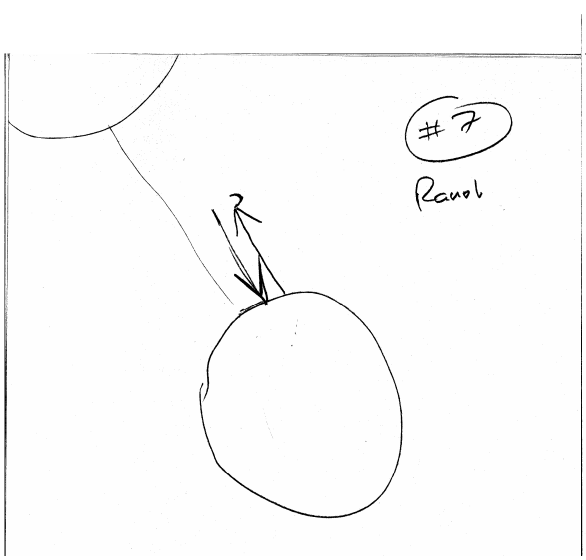
> I think the consensus is that humans are, appear to be enhancing the greenhouse effect. Um, I think it's a given among most scientists that now the, we are influencing the greenhouse effect, but the debate is more over, like, to what extent. From what I hear, we're enhancing it, but I know there are scientists that argue we've had almost no influence on it.

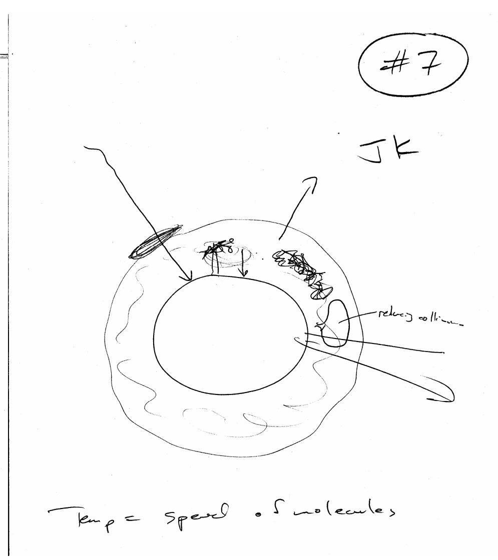
Item 12 provided possible diagrams of the greenhouse effect. Raoul picked the correct answer of Option D. He provided a clear explanation for each of the arrows shown for this option:

> [The] solid air incoming is the same on all graphs and then there's a dashed arrow pointing away from the surface of the Earth within the atmosphere that reflects like the Earth, like, radiating away energy. Um, some of the incoming energy from the Sun and the, ah, the solid air that will be reflected back. I think some of that will bounce around within the atmosphere which it contributes to the dashed arrow, ah, pointing back towards the Earth. And then additional energy is reflected away straight off the atmosphere.

The last question of the survey dealt with whether the greenhouse effect warms or cools the planet. Raoul selected Option A that the Earth is warmer due to temporary trapping. He knew that energy can't be destroyed and thought that the Earth radiates away less energy than it receives. "Earth keeps sending out energy and I think just because the Sun is a constant source of energy, and I think the Sun is increasing in intensity . . . over it's lifetime, . . . that still goes along with what I said earlier in the interview, and that energy is temporarily trapped in the atmosphere and just because I don't think there's anything that also can permanently trap energy."

At the end of the interview, the interviewer drew a picture of the Earth with an atmosphere. He also drew an arrow to represent energy coming into the Earth and an arrow going away. Raoul was asked to explain why some energy stays in the atmosphere and doesn't come straight back out. He did not know immediately. At first he wanted to say something about "stable form of energy" but he thought that wasn't correct. Next, he offered that "a gas would absorb energy better than nothing." When asked what would happen to a gas if it absorbs energy, Raoul explained that the "molecules start moving faster in relation to one another" and "it increases kinetic energy." This might lead to more energetic collisions, but the molecules would eventually cool down because "nothing can be a perfect absorber of energy, which has to do with one of the laws of thermodynamics." Finally, Raoul was asked what makes warm molecules cool down and how they get rid of their energy. Raoul mentioned that "one of the properties of gas is as it gets warmer, it expands. . . . So maybe that would have some sort of effect of reducing collisions and somehow letting the energy die out." At that point the interview was stopped.





Interview #8 with Farah on September 30, 2005 at 10AM

Farah was a freshman majoring in fine arts at the university. She had selected "non-science" on the survey. She had taken a chemistry class during junior year of high school that had covered the greenhouse effect quite a bit. She had really enjoyed the chemistry class, stating half-way through the interview, "I learned a lot from my parents and reading, but as far as the greenhouse effect goes, I think the majority of my education on that topic took place in that class." She did not have any other classes during the current semester dealing with the greenhouse effect, however she was playing with the idea of doing a ceramics project involving the greenhouse effect later in the semester.

At the outset of the interview, Farah was asked to explain and/or draw a description of the greenhouse effect. She first drew a section of the Earth with a stick person on it to represent the people emitting greenhouse gases, for example methane and CO_2. "These gases form like a foggy shield in the atmosphere, upper atmosphere . . . that tends to trap heat inside with layers, outer layer and the Earth, and creates increased temperatures and climate change." As she explained this, she included a second drawing to the right showing a shaded in shield. Humans emitted these gases by "driving automobiles, . . . burning carbon based materials, . . . agriculture, for several different reasons, . . . and industry."

When asked what she meant by a "foggy shield," she explained, "I do not remember the specific chemistry of any of this. Something about the shape of the molecules or the way they like to form or bond or shape themselves once they get into that upper atmosphere. They will create sort of, I don't even know if it's a visible haze, . . . but if it's just like a shield or something that is impenetrable by infrared heat that's being emitted or coming back off of the Earth, trying to get back out of the system." The interviewer also asked her to clarify what she meant by the "upper atmosphere," she first drifted away from this term and tried to explain that maybe it could be in the lower atmosphere as well ("above the ground, in the sky"). However, when the interviewer tried to clarify whether the shield was throughout the atmosphere, she said, "No, that's not the impression I get, but it's higher. So maybe upper, upper atmosphere is what I did want to say." She did not think the shield was something you could see with the naked eye, but "something that is impenetrable by a certain wavelength." She also confidently expressed that this shield blocked heat, which she also thought was probably infrared.

The interviewer next pursued a line of questioning to get at the location of the "shield" in the atmosphere and whether it was continuous with the ground or above the ground in a thin layer. In her responses, Farah first described, "I have a feeling that it starts, like, far above where we humans have developed at all." She then lifted the shield higher and higher, "above the buildings, . . . above everything, . . . above the ground, . . . probably above clouds, . . . it could be higher than airplanes." At first, she described that the shield was not continuous with the ground. But then she changed her description based upon a textbook image she remembered from chemistry five years before. She drew a donut shape to represent the Earth and a "dome around the Earth" that she shaded in all the way to the ground. The interviewer mentioned that he had seen this image on lots of surveys and was wondering if the greenhouse effect was occurring just at the top of the dome or throughout the atmosphere underneath. Farah explained that in her drawing, the top of the dome just signified the end of where the greenhouse effect was occurring. "All of those greenhouse gases doing what they do to hold that heat into there" occurred underneath the dome. So she was definitely describing a full atmosphere effect, not a specific section of the upper atmosphere.

At the end of this discussion, Farah offered an interesting side comment confirming that she is a very visual learner, "I tend to have a visual memory and the fact that I can back this up now with an image of any kind, I don't even know where it came from, I'm, I'm gonna go on that."

Farah had completed GECI.vB2, and so the interview proceeded with Item 21. For this, Farah selected infrared. She knew that she had learned the answer sometime before and was not entirely sure anymore, but she thought infrared was the best answer. She definitely did not associate the Sun with radio waves and x-ray waves. The remaining three choices were all contenders, but she associated "infrared with heat and the Sun with heat."

For Item 22, Farah selected carbon dioxide as the most abundant greenhouse gas. She had learned that methane was also a greenhouse gas, but not a particularly abundant one. She also thought that ozone was "a whole separate issue" even though it could still be a greenhouse gas. "I just sort of see greenhouse and the ozone layer as two separate things." For water vapor, she was inclined to say that it was most abundant and also knew that it was a greenhouse gas, but she still went with CO_2 as her final answer. Later on when the interview reached Item 27, she remembered distinctly the other four being referred to as greenhouse gases in her high school chemistry class, and she was 85-90% confident that oxygen was not a greenhouse gas.

For Item 23, she selected that the Earth's surface is mainly heated by infrared given off by the atmosphere, but she was less confident about this because of the term "atmosphere." She would have preferred a choice that said the surface is mostly heated by infrared from the Sun. She did not pick ultraviolet passing through the ozone layer because she didn't know if ultraviolet was the "main source of heat for the Sun and planet," and she did not select the answers involving cars and industry because "before cars and industry, this planet was still fairly well heated."

When answering Item 24, she first mentioned that she remembered being confused by this question when she took the survey earlier in the semester. "I remembered this one specifically and I remember thinking, 'Man, I don't like any of these answers at all.'" She talked through the question with the interviewer, expressing that the greenhouse effect definitely does not influence the flow of energy into the system. She initially thought it influenced the flow out of the system and eventually decided that it also affects the flow through the system as well, so she selected Option E. When asked what the question meant by the "Earth system" she drew a picture of a flat Earth with three concentric half-rings above it to represent several layers of atmosphere. "At some point, there's, like, an outermost layer of the atmosphere, and, I would think, from there on down would be considered the Earth's system."

Moving on to Item 25, Farah was again not inclined to select radio or x-ray for heating the upper atmosphere and was torn between the other three. She quickly eliminated visible and then stated, "For some reason, I want to say ultraviolet for this one, just because I understand that that's emitted quite a, quite a bit of ultraviolet energy is emitted from the Sun, but we're protected from it because of our stratosphere. That's the impression I get. So, I would say ultraviolet for this one. And the remaining energy that comes down to the Earth's surface would be infrared, so that would support my previously statement." This was her justification for choosing ultraviolet for heating the upper atmosphere and infrared for the lower atmosphere. Later in the interview, she also selected infrared for Item 33 regarding the energy that greenhouse gases interact most strongly with.

Item 28 involves the main mechanism for the greenhouse effect. Farah immediately eliminated the most popular distracter regarding the ozone hole and provided the following metacognitive justification. "I think I remember learning in, in school, in high school, or maybe even having this problem myself, but the issue of the ozone layer and the greenhouse effect are commonly considered to be just one and the same when, in fact, they're not." She eliminated Option E because she didn't think that hot air rising was part of the issue. She also eliminated Option A about heat given off by factories, although mentioned that she would have selected it if it had said "greenhouse gases released by factories and other industrial activities." Finally, she and wasn't initially inclined to select Option C regarding energy being absorbed and given off by gases because she couldn't "wrap my brain around that one well enough to consider it."

While discussing Option C for Item 28, Farah provided a quote regarding the complexity of the answer: "I'm just reluctant just because I don't know how to interpret being, like, energy being given off by gases after being absorbed in the atmosphere. That's a lot of things going on." This quote was intended to describe the complexity of the answer, but may also relate to the complexity of the actual greenhouse effect. In any event, Farah eventually selected Option D regarding pollution as the final answer "because that goes along with something I've understood about the greenhouse effect."

For Items 29 and 30 regarding the energy reflected and radiated by Earth's surface, she did not like radio and x-ray again, and quickly removed ultraviolet because she didn't think much ultraviolet made it through the atmosphere to the Earth's surface. She decided to pick infrared over visible for both answers. She was more confident about infrared being given off by the surface than she was for her answer regarding the energy reflected.

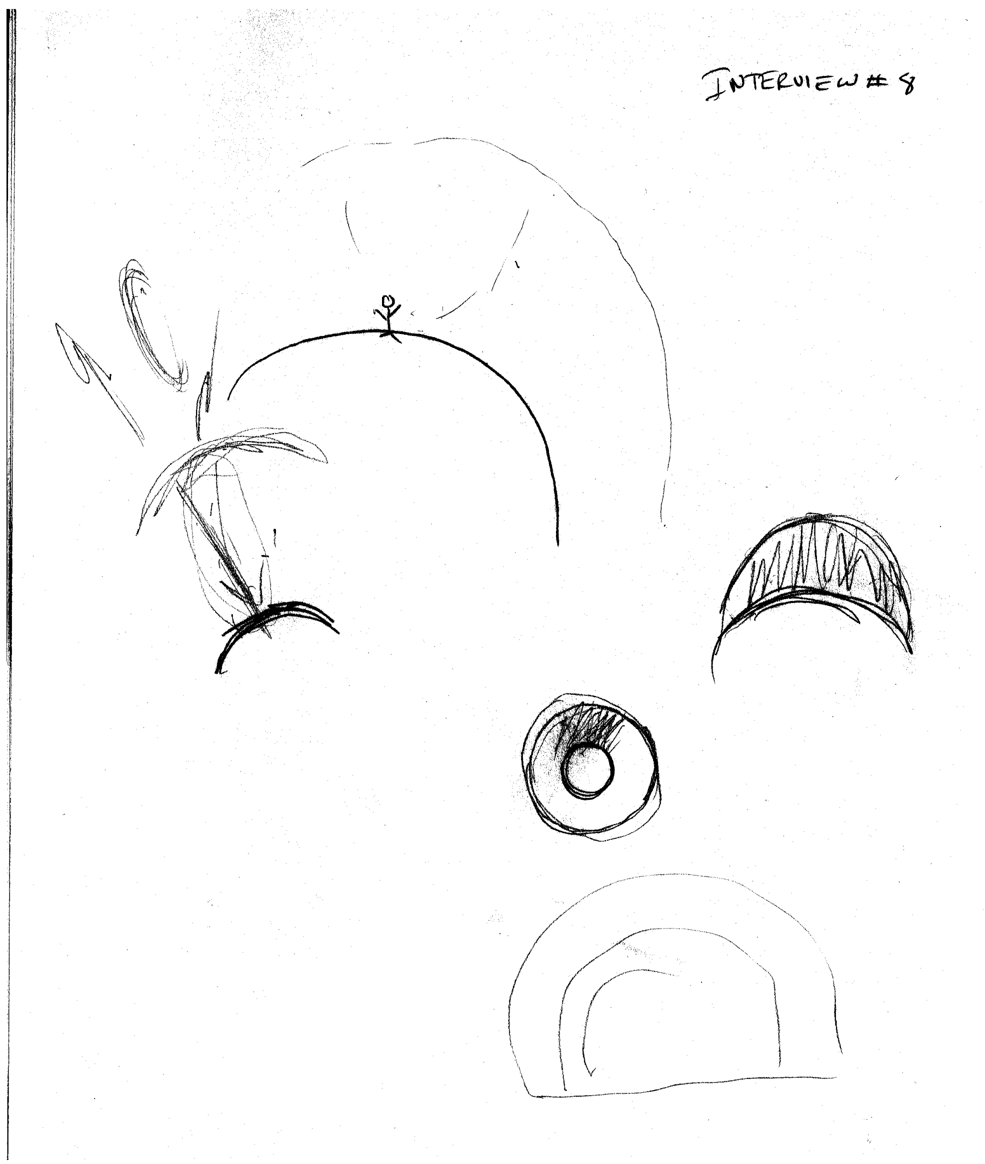
For Item 32 regarding human civilizations impact on the greenhouse effect, she selected Option A that the greenhouse effect is caused by naturally occurring gases. She thought Option B about plants was "too specific," and also she also described that plants turn a greenhouse gas into oxygen, which, as she had stated before, is not a greenhouse gas. She then provided a nice description regarding the natural greenhouse effect and the anthropogenic greenhouse effect:

> I think that it [the greenhouse effect] has a natural balance on the Earth, like before humans came to be on the planet. Um, it did exist, but to such a level, to such an extent that it didn't affect anything too drastically. It kept everything pretty stable, and the introduction of humans and industry has sort of taken it to a point where it's no longer maintaining its natural state of balance.

She thought the greenhouse effect has "been around for a while, as long as there have been greenhouse gases . . . which has been a long time." This reasoning provided a foundation for her selection of Option A for Item 34. In her mind, the greenhouse effect is a process that has been around a long time and it's "only recently that we've noticed an extreme change in it, in its overall effect on the Earth and we could attribute that to human activity."

Following this, the interviewer acknowledged that Farah seemed to have learned a lot about the greenhouse effect in her high school chemistry class. Farah also gave credit to conversations with her "very environmentally and politically active family" as a factor for reinforcing what she had learned in the chemistry class. The interviewer asked what she remembered about learning that the greenhouse effect is different from ozone depletion. She mentioned that the textbook was really good and the teacher was really good. She also mentioned that the teacher "liked to sing songs about all of these issues. .

. . Maybe that was the clincher." She also described that the class treated the two topics "as completely separate issues." She also thought that "he went in knowing that, knowing that a lot of us would have the misconception that they're one and the same thing, and we just concentrated on, on both of them, um, separately." She also remembered having debates on the issues, but did not remember doing any laboratory experiments specifically related to the greenhouse effect. Finally, she mentioned that "he liked to draw pictures," which may have helped Farah since she considered herself to be a visual learner. At this point, the interview ended.



Interview #9 with Elizabeth on September 30, 2005 at 2:10PM

Elizabeth was a freshman majoring in political science. She had touched upon the greenhouse effect in a class during middle school but not high school. She also had not covered the greenhouse effect in any classes yet that semester.

At the beginning of the interview, Elizabeth was asked to explain what was in her head when she thought about the greenhouse effect and to draw a picture if she wanted to. She provided a fairly characteristic ozone hole scenario to describe the greenhouse effect. She mentioned there was a "lot of controversy over it" and that "there are certain areas in the ozone which aren't completely full, so there's more rays from the Sun that's coming in." She drew a picture of a Sun in the lower left corner and an Earth in the middle with "ozone around it" and explained that there are holes in the ozone caused by pollution that we have put in the air from factories and cars and "because there's these holes, we're getting more sunlight coming in." This was "hurting the planet" and causing polar ice caps to melt faster and was "bad for the environment overall." However, she stated that she did not know much more and that she didn't know "what kind of rays are coming in or why exactly it's bad." When asked later on about the effects of the greenhouse effect, she re-emphasized melting of polar ice caps and also that too much exposure to sunlight was bad for human skin and could lead to skin cancer.

By ozone or the ozone layer, she initially meant "the atmosphere of Earth" and described that it keeps rays from coming into the planet. When questioned, she then said the ozone was "part of the atmosphere," because there were also other parts, like pollutants. The interviewer also clarified that she thought ozone was a component that was spread throughout the atmosphere, not a specific layer. On the drawing, Elizabeth drew that she thought ozone was more concentrated towards the surface of the Earth and thinned out as you went higher into the atmosphere, confirming her model that ozone is part of the atmosphere and follows the density profile of the atmosphere.

The interviewer next asked her to draw what a hole in the ozone might look like. She drew a divot in the upper atmosphere towards the left of the picture and then crossed this out saying that it "wouldn't look like a normal hole." Instead, at the top of the picture she drew in an atmosphere that was closer to the surface of the Earth and explained "I'm guessing it would just be where it's thin, like instead of expanding like all the way out here." At a hole, the atmosphere would be thinner and would allow more light to penetrate "because there's not as much defense."

Before launching into the survey items, the interviewer asked Elizabeth if she drew any distinctions between ozone depletion, the greenhouse effect, and global warming. She replied, "Pretty much, well, they're not exactly the same, but dealing with the same issue." She then explained that she thought ozone depletion was the holes in the atmosphere she had just described. Global warming was the fact that it was becoming warmer on the planet and ice caps were melting because of the "extra sunlight we're getting and it's staying in the atmosphere." She was not exactly sure when it came to the greenhouse effect, however. She tapped her pencil and said she knew it "pertains to this whole subject and to these two [ozone depletion and global warming], but I don't think I could explain it to you on why they use this, like, metaphor." After thinking more about it, she described that if you live in Alaska, you raise plants in a greenhouse because that's where they stay warm. She drew a picture of a greenhouse and an arrow from greenhouse effect to global warming, explaining that "it could pretty much be the same thing as this because it's the greenhouse and, if we're getting all this extra, um, heat in our, in our atmosphere, and it's stuck in there, so, I think it sorta goes with this one [global warming]." She thought that maybe plant greenhouses were a metaphor for global warming which results from ozone depletion.

Finally, the interviewer pointed out that Elizabeth had introduced a new concept in her last description, that the energy "gets stuck in the atmosphere." This caused confusion for Elizabeth and she admitted that this (along with the hole in the atmosphere) was somewhat contradicting. However, she reaffirmed "Here's this thing. We know it's coming in because we have this depletion, but it's staying in the atmosphere longer." She had trouble with the word "stuck" though, stating "I don't think stuck is the right word to say. . . . It's not getting stuck; it's just staying longer." She had a lot of trouble with the term stuck, and firmly established, “Stuck is definitely not the right word, but it’s in the atmosphere longer and it’s warmer because we have the extra sunlight coming in.”

The interview then turned to Items 1 through 14 of GECI.vB1. For Item 1, Elizabeth selected that the Sun gives off mostly ultraviolet and infrared. She was vague about ultraviolet light, stating it “is a form of light that we have a lot of.” For infrared, she referenced that you can see it with special equipment. When asked which of the two was more important, she picked ultraviolet because she thought it was “the predominant one.”

For Item 2, she selected hydrogen and helium as the most abundant greenhouse gases. Her mental construct for answering this question was that she was looking for the gases that she thought were “bad.” The greenhouse effect stem had “a negative connotation” for her, and she was looking for gases that also had a negative connotation. Interestingly, carbon dioxide sounded like “one of those normal gases that are in the atmosphere because it’s something that we give off and we use, so I automatically thought that that is not bad. The same thing with oxygen.” Hydrogen and helium, however, sounded “harmful” to her and she knew that hydrogen was “pretty powerful.” When asked about ozone, she explained that she was thinking “if this [ozone] was part of the atmosphere, it’s obviously something that’s been there and good, so that’s why I didn’t pick that one.” She eliminated all of the other choices besides hydrogen and helium because they sounded like “something that we have in our atmosphere that hasn’t hurt it before.”

Item 3 involves the forms of energy heating the Earth’s surface. She initially selected visible and ultraviolet, but explained that this was not her first instinct. Her first instinct was to select ultraviolet and infrared based upon her answer to Item 1. She definitely thought ultraviolet could do a lot of heating. She quickly questioned her choice of visible, though, mentioning that visible “helps us see colors and stuff, that’s what I think of when I read it, but that wouldn’t exactly heat the Earth.” She confidently eliminated Options A and E because she didn’t see x-ray and radio as forms of energy that would heat the Earth. “It’s there, but I just don’t see them having enough power, I guess to heat the Earth." She was not sure about infrared but eventually went with her first instinct and selected it along with ultraviolet.

There was a long pause in the interview as Elizabeth considered Item 4 regarding the total amount of energy leaving space. She then stated that she thought the correct answer was D – that it depended upon the concentration of greenhouse gases in the atmosphere. She explained that she initially thought the right answer was Option B (that less energy leaves than arrives), but that Options D and E provided explanations that she liked better. She presented reasoning that supported Option E, stating "when it comes in, that would depend on the status of the ozone, because of, of how much light it's letting in." She also provided somewhat convoluted reasoning to support Option D, explaining "we know that greenhouse gases are an issue, so if there's more in the atmosphere then it makes it harder for the energy to escape and that would be why it's staying longer and there's more heat, because we're getting more than is able to escape quick enough because of the gases that are in the atmosphere." The interviewer asked if greenhouse gases were affecting the ozone or something else. She visualized the greenhouse gases sitting all around the atmosphere and not being able to get out, but she wasn't sure if these were the same gases that were affecting the ozone. She provided a second drawing of the Earth (inner circle of figure at end of summary) with ozone around it (outer circle in figure). She then scribbled all around the Earth and described that these were the greenhouse gases that were stuck all around. She then wrote in energy with an arrow and explained that "that's why it's harder for it to go out, the energy." She clarified to the interviewer that the scribbled lines were above ground and in the air, but that it was in the lower atmosphere, "underneath the ozone, . . . like in the sky." Here, she described that the greenhouse gases were probably below the ozone and that she did not know whether or not they affected each other.

The interview then moved on to Item 5. Elizabeth selected ultraviolet energy as primarily heating Earth's atmosphere based upon her answer to Item 1.

For Item 6 regarding human sources of greenhouse gases, she narrowed it down to either agricultural activities or use of synthetic fertilizers, and selected the latter. She eliminated the other options because they "were all things that would put pollution into the air." She struggled with the other two because neither seemed like they would "put pollution into the air that would hurt the environment." She marginally eliminated the agriculture option because she associated growing rice with pesticides and chemicals that wouldn't be good. She was 90% confident that the answer was fertilizer "because that seemed like something that wouldn't have anything to do with any kind of pollutant or something that would harm the atmosphere."

When discussing nuclear power plants, Elizabeth had mentioned that they give off "gross pollution." When asked to clarify this, she associated the smoke coming out of factories with whatever is going on inside a nuclear power plant. She thought that the power plant must be "running all kinds of machinery and doing what they need to do. But it gives off a lot of, just, pollutants," although she was not sure what kinds.

Moving on to Item 7, Elizabeth selected that greenhouse gases influence surface temperatures by concentrating smog and pollutants over cities. This was consistent with her drawing that greenhouse gases stay concentrated and don't allow energy to leave. She mentioned that unpopulated cities could also be influenced, just not as much as populated cities which would have more smog and pollutants. She liked the word "concentrating" in the answer and thought that the pollutants and smog would affect the temperature "because less is leaving." Elizabeth was also asked if she would select any other options for Item 7 if the question was changed to "circle all that apply." She decided she would also select Option A (destroying the ozone layer) and maybe Option D (magnifying sunlight) but definitely not the other two options involving photosynthesis and the flow of energy through the atmosphere.

Items 8 through 10 involve reflected and radiated light from the surface of Earth during day and night. For all of these questions, Elizabeth expressed frustration that there was not much logic that she could put into the answer. She selected ultraviolet for Item 8 and infrared for Item 9 because these were the answers she had given for Item 1. She had did not distinguish between reflection and radiation of light and simply picked the two most abundant forms of light in her mind. She acknowledged that this did not necessarily mean it would also be reflected or radiated the most by the surface, but she couldn't come up with any other logic for answering either question. She similarly had no idea for Item 10. She surprisingly selected visible light as being given off during the nighttime, because it was the "kind of light that lets us see like colors." When asked if there was a lot of light coming from the Earth at the night, she admitted that her answer didn't make sense, but she stayed with the answer of visible anyway.

In the interest of time, the interview then skipped to Item 12 with diagrams for the greenhouse effect. Elizabeth liked Option D the best because it had energy coming in, energy coming up into the atmosphere, and energy bouncing back because of "greenhouse gases that are in the way." In addition, she liked that some of the energy was still able to come out. She didn't think it was "possible for it all to stay in there, or else it would be a lot warmer, so some of it is still escaping and getting out." When asked which of the arrows in Option D were most affected by the greenhouse effect, she selected both of the outgoing arrows (from the surface to the atmosphere and from the atmosphere to space). Both of the arrows were affected by greenhouse gases. Of these, she thought the arrow leaving to space was less affected, though, because "it's not that congested that it's not leaving." She also agreed that the arrow from the atmosphere back to the surface was also affected; she interpreted this arrow as "energy that's bouncing back because of the gases that are here [in the atmosphere]."

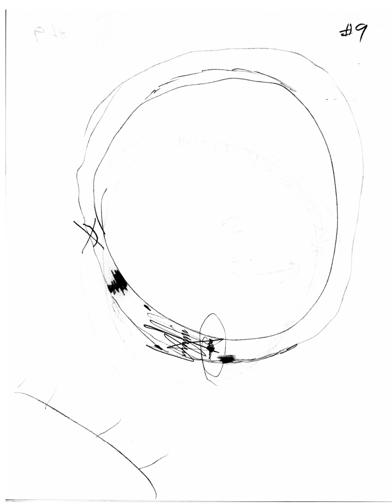
Despite her initial explanation of the greenhouse effect which involved more incoming sunlight, she was not sure how the greenhouse effect influenced the arrow coming in from space. After she was reminded of her initial explanation at the beginning of the interview which involved ozone depletion, she provided a statement that reflected a cognitive shift in her thinking about these two phenomena:

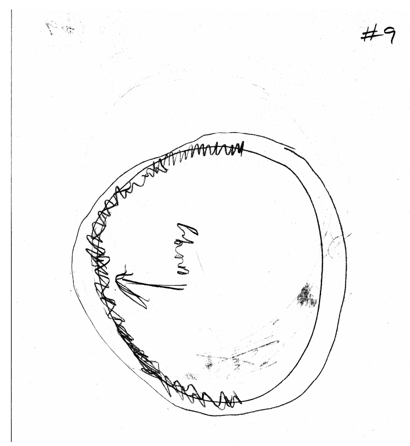
> I guess that all depends, going back to the, like, the definitions we discussed earlier because if it's all connected, whereas the ozone depletion, which is where I see this arrow as, how much light is coming in, whether that's affected by, um, the greenhouse gases. So I guess it, it depends if these gases, 'cause they're the ones keeping, um, the Earth warmer. But if they're also the gases that are, um, depleting the ozone, then it would be connected. But it might be two separate issues that are put together

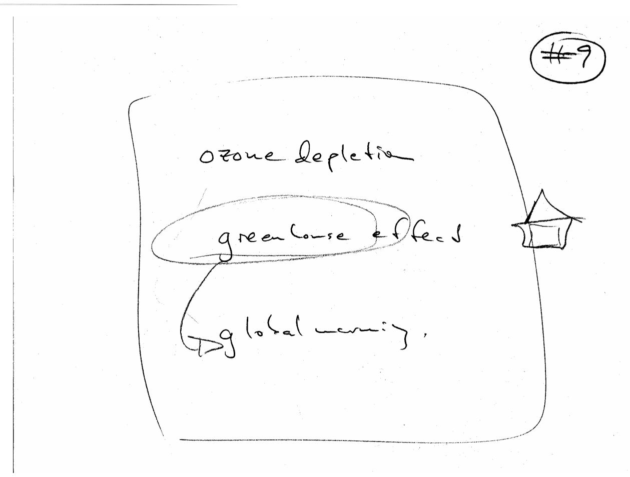
> because it's all, like, in the atmosphere. But I don't know, so I could not tell you.

Item 14, about whether the greenhouse effect makes the planet warmer or colder, was the last item on the survey. Elizabeth selected Option A, that the Earth was getting warmer due to temporary trapping, because she didn't "think all of it gets trapped so it's not permanently trapped here. I'm sure some of it still makes it out or else we'd be getting warmer and warmer and warmer, but we're getting slowly warmer."

There was time for one last question during the interview. The interviewer asked Elizabeth if she thought the greenhouse effect was a good thing, a bad thing, or a neutral thing. She confidently stated it was a bad thing, explaining that she had only heard of it being a negative thing and never heard anybody saying it was a positive thing. At this point the interview ended.







APPENDIX L: LECTURE TUTORIAL ACTIVITY

During the Spring 2006 semester, the following Lecture Tutorial (LT) activity was tested using Survey GECI.vC (see Appendix M). Sections 4.3 and 4.7 and Table 4.9 provide details regarding the implementation of the LT activity.

Initials:	____ ____ ____
Month / Day of Birth:	____ ____/ ____ ____

Energy Flow through the Atmosphere and the Greenhouse Effect

Section 1: The solar spectrum

Objects give off different amounts of light depending upon their temperature. Figure 1 below shows the energy spectrum for our Sun along with the percent of energy given off by the Sun in the ultraviolet (UV), visible (VIS), and infrared (IR) portions of the electromagnetic spectrum.

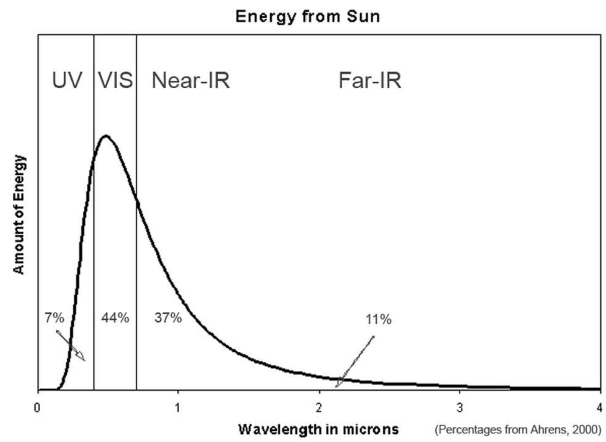


Figure 1

1) Which TWO forms of light account for the majority of energy coming from the sun: ultraviolet, visible, or infrared? Which of the three accounts for the least energy? Provide numbers to back up your answer.

2) Based upon Figure 1, why is ultraviolet light NOT an important energy source for heating the surface of the Earth?

3) Consider the following debate between two students regarding the energy given off by the Sun.

Student #1 – I think that the Sun gives off most of its energy at ultraviolet wavelengths because ultraviolet light is more intense than visible light and you always hear about ultraviolet light causing sunburns.

Student #2 – Even though UV photons are more energetic than visible photons, the Sun simply gives off less ultraviolet photons and gives off way more visible and infrared photons. So I think that these longer wavelength photons account for most of the energy coming from the Sun.

Do you agree and/or disagree with either of these students? Explain your reasoning.

Section #2: Atmospheric absorption of light

Earth's surface temperature is affected by energy that is absorbed at the surface. However, a photon's ability to travel through our atmosphere and reach the ground depends upon its wavelength. Figure 2 below shows that certain energies of light are absorbed in our atmosphere more than others. The figure also lists the primary gas molecules responsible for the absorption.

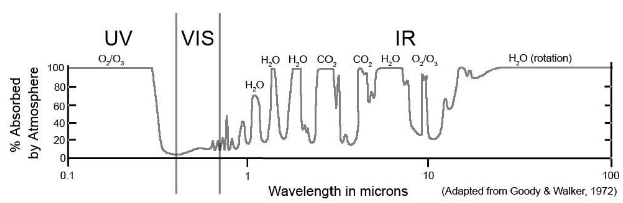


Figure 2

4) What gas molecules are primarily responsible for the absorption of each of the following forms of light in our atmosphere?

Type of Light	Molecule(s) Responsible for Absorption
Ultraviolet	
Visible	
Infrared	

5) Comparing the visible and the infrared parts of the spectrum, which would you say has an easier time getting through our atmosphere? Which experiences more absorption?

Section 3: Spectrum from Earth's surface

Once visible light from the Sun reaches the surface of Earth, it can either be reflected back towards space as visible light or be absorbed by the ground. Reflected light does not change the temperature of the surface, while absorbed light causes the temperature of the surface to increase. Ground that is heated then gives off infrared light based upon its increased temperature. As an example, black asphalt absorbs more visible light and gives off more infrared light than a white sidewalk on a hot day.

6) The Sun is approximately 6000K at the surface and gives off most of its energy as visible light; the Earth's surface is much cooler at about 288K. What type of light do you think the Earth's surface gives off: ultraviolet, visible, or infrared light? Explain your reasoning.

7) Does Earth's surface give off light at night? If so, what type? If not, why not?

8) Consider the following debate between two students regarding the energy given off by Earth's surface.

   Student #1 – The Sun mainly gives off visible light and so does Earth's surface because I can see it during the daytime.

   Student #2 – But that's just reflected sunlight. Earth's surface is much cooler than the Sun and mostly gives off energy closer to the kind that our bodies give off – infrared light. I'm not sure, but I think the surface probably radiates infrared light during both the daytime and the nighttime based upon its temperature.

   Do you agree and/or disagree with either of these students? Explain your reasoning.

9) Based upon your answer to Question 5, will the light given off by Earth's surface easily travel back through the atmosphere to space or will it be absorbed by molecules in the atmosphere? Explain your reasoning.

Section 4: Energy flow and the greenhouse effect

Figure 3 below shows the flow of energy originally from the Sun through the Earth system (surface and atmosphere). The numbers listed describe the rate of energy flow through system (units of watts per square meter). A larger number indicates that more energy is flowing through that labeled pathway.

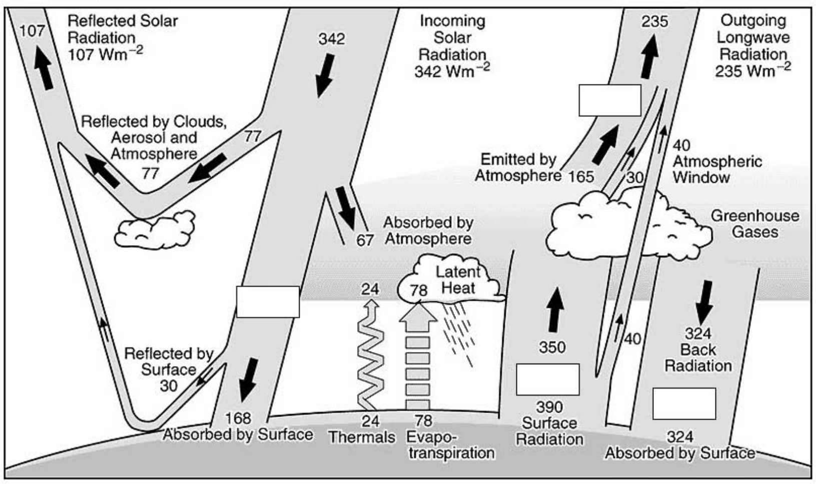


Figure 3

10) In Figure 3, fill in the four empty boxes with the type of light involved: UV, visible, or IR.

11) What two types of light primarily heat Earth's surface. What one type of light primarily heats Earth's atmosphere?

12) Is more energy absorbed by the Earth's surface in the form of light from the Sun or light from the atmosphere? Provide values to justify your answer.

13) Due to the energy absorbed by Earth's surface from the atmosphere, is the surface temperature warmer or cooler than it would be without this energy input?

14) How does the total rate of energy coming in from space (incoming solar energy) compare to the total rate of energy leaving out to space (all energy reflected or given off by earth and atmosphere)? Provide values to justify your answer.

15) Based upon your answer to Question 14, does the total energy in the Earth system increase, decrease, or stay the same over short time scales? Explain your reasoning.

The flow of energy shown in Figure 3 is the source of the natural "atmospheric greenhouse effect." Visible light penetrates the atmosphere and is absorbed by the surface. The heated surface gives off infrared light that is then absorbed by the atmosphere. The heated atmosphere gives off infrared light out to space and also back down to Earth's surface, making the surface temperature warmer than it would be without a greenhouse effect. The amount of energy entering and leaving the Earth system is balanced, but the Earth's surface temperature is warmer because the surface is heated both by visible light from the Sun and infrared light from the atmosphere.

16) In Question 4, you listed several gases. Which of these are primarily responsible for absorbing and emitting infrared light? What characteristic makes them greenhouse gases?

17) Consider the following debate between two students regarding the greenhouse effect.

Student #1 - So the greenhouse effect is caused by infrared light being trapped in Earth's atmosphere by greenhouse gases. Visible light from the sun heats the ground, but the infrared light given off by the ground gets permanently trapped in the atmosphere and can never escape.

Student #2 – I think that's close. But based on Figure 3, all of the arrows balance and just as much energy leaves the planet as comes in. I think the greenhouse effect makes the surface hotter than it would be without greenhouse gases because the ground gets visible light from the Sun AND infrared light from the atmosphere given off back to the surface.

Do you agree and/or disagree with each of these students? Explain your reasoning.

APPENDIX M: GREENHOUSE EFFECT CONCEPT INVENTORY, VERSION C

This appendix provides a copy of Survey GECI.vC administered during Fall 2005. There was only one version of this survey instrument. See Section 3.1.3 for further details.

Results from GECI.vC survey items are discussed throughout Chapter 3 and listed in Appendix N.

On the scantron sheet, bubble in the best answer for each question. Please do not write on this survey.

1) Which of the following is the most abundant greenhouse gas?
   a) carbon dioxide (CO_2)
   b) water vapor (H_2O)
   c) methane (CH_4)
   d) oxygen (O_2)
   e) ozone (O_3)

2) Earth's atmosphere is warmer than it would be without a greenhouse effect. Which form of energy is absorbed by the atmosphere and mainly causes this increased temperature?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

3) On average, the total amount of energy leaving the Earth system to space
   a) is greater than the amount of energy arriving from space.
   b) is less than the amount of energy arriving from space.
   c) is roughly equal to the amount of energy arriving from space.
   d) depends upon the concentration of greenhouse gases in the atmosphere.
   e) depends upon the status of ozone in the atmosphere.

4) Which of the following is a primary characteristic of greenhouse gases?
   a) They can destroy certain molecules in the atmosphere.
   b) They bend and magnify sunlight entering the atmosphere.
   c) They can trap certain molecules in the atmosphere.
   d) They can bounce around more in the atmosphere.
   e) They are transparent to some forms of energy but not all.

5) The greenhouse effect is a very ______ process probably caused by ______.
   a) recent ; burning of fossil fuels, industry, agriculture, and other human activities.
   b) old ; plants that increase humidity and create conditions similar to those in a greenhouse found at a plant nursery.
   c) recent ; depletion of the ozone layer which allows more ultraviolet sunlight to reach the Earth's surface.
   d) old ; interactions between naturally occurring gases and various forms of energy in the atmosphere.
   e) recent ; natural processes including volcanic emission and changes in solar activity.

6) During the nighttime, Earth's surface mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) Earth's surface does not give off energy during the nighttime

7) Which of the following most strongly affects Earth's overall surface temperature?
   a) heat released by factories and other industrial activities
   b) the destruction of the ozone layer allowing more sunlight into the atmosphere
   c) the flow of different forms of energy through the atmosphere
   d) air pollution trapped in the atmosphere by gases
   e) sunlight being magnified and focused by gases in the atmosphere

8) Which one of the following is <u>not</u> a greenhouse gas?
   a) carbon dioxide (CO_2)
   b) water vapor (H_2O)
   c) methane (CH_4)
   d) oxygen (O_2)
   e) ozone (O_3)

9) Which of the following best describes the relationship between the greenhouse effect and global warming?
   a) The greenhouse effect and global warming are the same thing.
   b) An increase in the greenhouse effect may be causing global warming.
   c) Global warming may be causing an increase in the greenhouse effect.
   d) The greenhouse effect and global warming are likely unrelated.
   e) There is no definite proof that either the greenhouse effect or global warming exist.

10) The Sun mainly gives off (radiates) which two forms of energy?
   a) ultraviolet and x-ray
   b) ultraviolet and infrared
   c) visible and ultraviolet
   d) infrared and visible
   e) radio and infrared

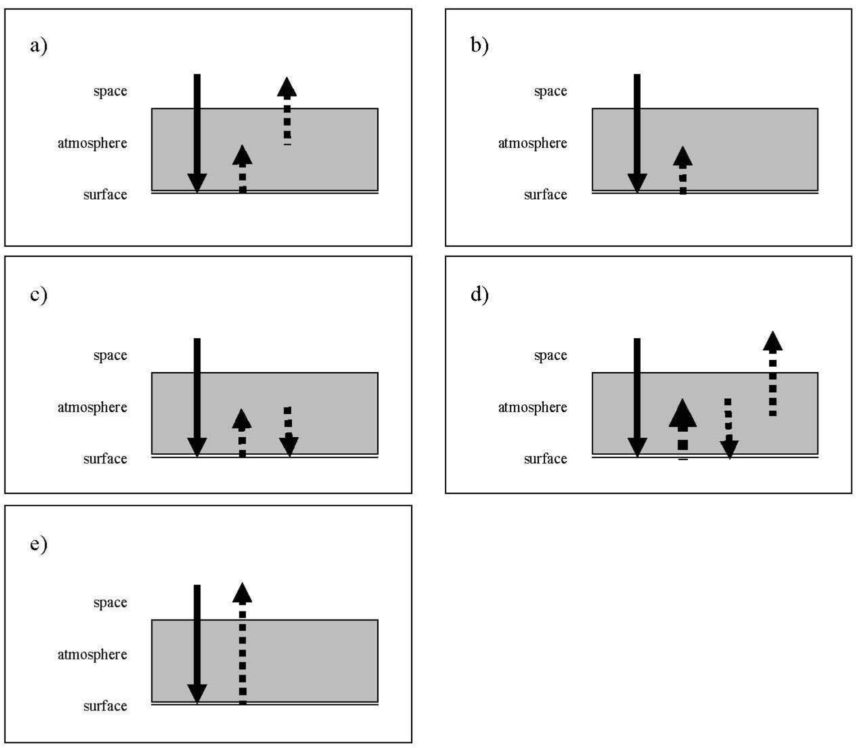
11) A planet that has a greenhouse effect
   a) receives more UV sunlight because it lacks ozone in its atmosphere.
   b) has an atmosphere that absorbs and then gives off certain forms of energy but not all.
   c) receives more energy because it is closer to its central star.
   d) has an altered atmosphere due to living organisms.
   e) does not radiate any energy away into outer space.

12) Earth's surface is heated mainly which two forms of energy?
   a) ultraviolet and x-ray
   b) ultraviolet and infrared
   c) visible and ultraviolet
   d) infrared and visible
   e) radio and infrared

13) If human civilization had never developed on Earth, would there be a greenhouse effect?
   a) Yes, the greenhouse effect is caused by naturally occurring gases in the atmosphere.
   b) Yes, the greenhouse effect is caused by plants giving off gases during photosynthesis.
   c) No, the greenhouse effect is caused by humans burning fossil fuels and releasing pollutants.
   d) No, the greenhouse effect is caused by humans depleting ozone in the atmosphere.
   e) No, there is no conclusive evidence that a greenhouse effect exists.

14) At which of the following does the Sun give off (radiate) energy at its maximum intensity?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

15) Each diagram below shows Earth's surface, the atmosphere, and outer space. The solid arrow represents incoming energy from the Sun that is absorbed by the surface. The dashed arrow represents energy that is radiated or given off by the surface and atmosphere. The thickness of the arrow roughly represents the amount of energy. Select the diagram that best represents the transport of energy.



16) Which of the following are the two most abundant greenhouse gases in Earth's atmosphere?
   a) carbon dioxide (CO_2) and methane (CH_4)
   b) ozone (O_3) and carbon dioxide (CO_2)
   c) nitrogen (N_2) and oxygen (O_2)
   d) oxygen (O_2) and carbon dioxide (CO_2)
   e) water vapor (H_2O) and carbon dioxide (CO_2)

17) Earth's atmosphere mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) Earth's atmosphere does not give off energy

18) Due to the greenhouse effect, Earth's overall surface temperature is affected primarily by
   a) an increase in energy entering from space.
   b) a decrease in energy leaving to space.
   c) both an increase in energy entering from and a decrease in energy leaving to space.
   d) energy being permanently trapped in the atmosphere.
   e) an increase in the amount of energy absorbed and given off between the surface and atmosphere.

19) You walk from a region of shade into a region of direct sunlight and notice you start to feel warmer. Which of the following most correctly describes the cause of the temperature increase?
   a) You absorb more ultraviolet energy than you give off (radiate) as visible energy.
   b) You absorb more visible energy than you give off (radiate) as infrared energy.
   c) You reflect more ultraviolet energy than you give off (radiate) as infrared energy.
   d) You reflect more visible energy than you give off (radiate) as infrared energy.
   e) You reflect more infrared energy than you give off (radiate) as visible energy.

20) During the daytime, Earth's surface mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) Earth's surface does not give off energy during the daytime

21) What is your gender?
   a) Male
   b) Female

22) What year are you in university?
   a) Freshman
   b) Sophomore
   c) Junior
   d) Senior
   e) Other

23) Which of the following best characterizes your academic major?
   a) Undeclared
   b) Non-science
   c) Science
   d) Engineering / Math
   e) Other

24) Prior to this semester, which of the following best describes your previous coursework?
   a) I have never taken a class that covers the greenhouse effect.
   b) In high school, I took a class that briefly touched upon the greenhouse effect.
   c) In high school, I took a class that dealt extensively with the greenhouse effect.
   d) In college, I took a class that briefly touched upon the greenhouse effect.
   e) In college, I took a class that dealt extensively with the greenhouse effect.

25) Have any of your other classes besides this course covered the greenhouse effect during this semester?
   a) Yes
   b) No

26) During this semester, did you consent to voluntarily complete an additional activity that may have been presented to your class on the greenhouse effect?
   a) Yes
   b) No

Thank you for your participation.
Please wait for instructions on returning survey.

APPENDIX N: GECI.VC RESPONSE FREQUENCIES

This appendix provides the response frequencies for each of the items on Survey GECI.vC (see Appendix M). A table is provided for each item listing the number and percentage of students who selected each response option listed both pre- and post-instruction. As described in Section 3.1.3, all six classes surveyed with this instrument directly treated the topic of the greenhouse effect.. Results from all six classes have been combined here.

See Appendix M and Section 3.1.3 for more details on survey administration.

GECI.vC * Q1 Crosstabulation

			Q1					
			A	B	C	D	E	Total
GECI.vC	0 - Pre	Count	367	71	11	67	40	556
		% within GECI.vC	66.0%	12.8%	2.0%	12.1%	7.2%	100.0%
	1 - Post	Count	194	164	7	23	11	399
		% within GECI.vC	48.6%	41.1%	1.8%	5.8%	2.8%	100.0%
Total		Count	561	235	18	90	51	955
		% within GECI.vC	58.7%	24.6%	1.9%	9.4%	5.3%	100.0%

GECI.vC * Q2 Crosstabulation

			Q2					
			A	B	C	D	E	Total
GECI.vC	0 - Pre	Count	7	119	24	396	10	556
		% within GECI.vC	1.3%	21.4%	4.3%	71.2%	1.8%	100.0%
	1 - Post	Count	3	236	33	126	2	400
		% within GECI.vC	.8%	59.0%	8.3%	31.5%	.5%	100.0%
Total		Count	10	355	57	522	12	956
		% within GECI.vC	1.0%	37.1%	6.0%	54.6%	1.3%	100.0%

GECI.vC * Q3 Crosstabulation

			Q3					
			A	B	C	D	E	Total
GECI.vC	0 - Pre	Count	45	216	120	91	83	555
		% within GECI.vC	8.1%	38.9%	21.6%	16.4%	15.0%	100.0%
	1 - Post	Count	21	103	223	40	12	399
		% within GECI.vC	5.3%	25.8%	55.9%	10.0%	3.0%	100.0%
Total		Count	66	319	343	131	95	954
		% within GECI.vC	6.9%	33.4%	36.0%	13.7%	10.0%	100.0%

GECI.vC * Q4 Crosstabulation

			Q4					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	135	114	244	21	42	556
		% within GECI.vC	24.3%	20.5%	43.9%	3.8%	7.6%	100.0%
	1 - Post	Count	39	56	194	38	72	399
		% within GECI.vC	9.8%	14.0%	48.6%	9.5%	18.0%	100.0%
Total		Count	174	170	438	59	114	955
		% within GECI.vC	18.2%	17.8%	45.9%	6.2%	11.9%	100.0%

GECI.vC * Q5 Crosstabulation

			Q5					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	195	64	131	151	12	553
		% within GECI.vC	35.3%	11.6%	23.7%	27.3%	2.2%	100.0%
	1 - Post	Count	66	35	35	250	11	397
		% within GECI.vC	16.6%	8.8%	8.8%	63.0%	2.8%	100.0%
Total		Count	261	99	166	401	23	950
		% within GECI.vC	27.5%	10.4%	17.5%	42.2%	2.4%	100.0%

GECI.vC * Q6 Crosstabulation

			Q6					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	74	294	40	82	66	556
		% within GECI.vC	13.3%	52.9%	7.2%	14.7%	11.9%	100.0%
	1 - Post	Count	26	316	21	20	17	400
		% within GECI.vC	6.5%	79.0%	5.3%	5.0%	4.3%	100.0%
Total		Count	100	610	61	102	83	956
		% within GECI.vC	10.5%	63.8%	6.4%	10.7%	8.7%	100.0%

GECI.vC * Q7 Crosstabulation

			Q7					
			A	B	C	D	E	Total
GECI.vC	0 - Pre	Count	26	243	111	61	113	554
		% within GECI.vC	4.7%	43.9%	20.0%	11.0%	20.4%	100.0%
	1 - Post	Count	15	92	179	40	73	399
		% within GECI.vC	3.8%	23.1%	44.9%	10.0%	18.3%	100.0%
Total		Count	41	335	290	101	186	953
		% within GECI.vC	4.3%	35.2%	30.4%	10.6%	19.5%	100.0%

GECI.vC * Q8 Crosstabulation

			Q8					
			A	B	C	D	E	Total
GECI.vC	0 - Pre	Count	11	113	168	140	124	556
		% within GECI.vC	2.0%	20.3%	30.2%	25.2%	22.3%	100.0%
	1 - Post	Count	5	28	151	101	114	399
		% within GECI.vC	1.3%	7.0%	37.8%	25.3%	28.6%	100.0%
Total		Count	16	141	319	241	238	955
		% within GECI.vC	1.7%	14.8%	33.4%	25.2%	24.9%	100.0%

GECI.vC * Q9 Crosstabulation

			Q9					
			A	B	C	D	E	Total
GECI.vC	0 - Pre	Count	41	373	94	24	24	556
		% within GECI.vC	7.4%	67.1%	16.9%	4.3%	4.3%	100.0%
	1 - Post	Count	15	265	71	43	6	400
		% within GECI.vC	3.8%	66.3%	17.8%	10.8%	1.5%	100.0%
Total		Count	56	638	165	67	30	956
		% within GECI.vC	5.9%	66.7%	17.3%	7.0%	3.1%	100.0%

GECI.vC * Q10 Crosstabulation

			Q10 A	Q10 B	Q10 C	Q10 D	Q10 E	Total
GECI.vC	0 - Pre	Count	69	216	216	44	11	556
		% within GECI.vC	12.4%	38.8%	38.8%	7.9%	2.0%	100.0%
	1 - Post	Count	16	99	138	143	3	399
		% within GECI.vC	4.0%	24.8%	34.6%	35.8%	.8%	100.0%
Total		Count	85	315	354	187	14	955
		% within GECI.vC	8.9%	33.0%	37.1%	19.6%	1.5%	100.0%

GECI.vC * Q11 Crosstabulation

			Q11 A	Q11 B	Q11 C	Q11 D	Q11 E	Total
GECI.vC	0 - Pre	Count	198	201	24	102	31	556
		% within GECI.vC	35.6%	36.2%	4.3%	18.3%	5.6%	100.0%
	1 - Post	Count	49	281	19	47	4	400
		% within GECI.vC	12.3%	70.3%	4.8%	11.8%	1.0%	100.0%
Total		Count	247	482	43	149	35	956
		% within GECI.vC	25.8%	50.4%	4.5%	15.6%	3.7%	100.0%

GECI.vC * Q12 Crosstabulation

			Q12 A	Q12 B	Q12 C	Q12 D	Q12 E	Total
GECI.vC	0 - Pre	Count	29	222	198	91	16	556
		% within GECI.vC	5.2%	39.9%	35.6%	16.4%	2.9%	100.0%
	1 - Post	Count	9	109	76	194	12	400
		% within GECI.vC	2.3%	27.3%	19.0%	48.5%	3.0%	100.0%
Total		Count	38	331	274	285	28	956
		% within GECI.vC	4.0%	34.6%	28.7%	29.8%	2.9%	100.0%

GECI.vC * Q13 Crosstabulation

			Q13					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	207	95	154	80	18	554
		% within GECI.vC	37.4%	17.1%	27.8%	14.4%	3.2%	100.0%
	1 - Post	Count	258	58	54	28	2	400
		% within GECI.vC	64.5%	14.5%	13.5%	7.0%	.5%	100.0%
Total		Count	465	153	208	108	20	954
		% within GECI.vC	48.7%	16.0%	21.8%	11.3%	2.1%	100.0%

GECI.vC * Q14 Crosstabulation

			Q14					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	16	90	68	312	70	556
		% within GECI.vC	2.9%	16.2%	12.2%	56.1%	12.6%	100.0%
	1 - Post	Count	12	80	124	152	32	400
		% within GECI.vC	3.0%	20.0%	31.0%	38.0%	8.0%	100.0%
Total		Count	28	170	192	464	102	956
		% within GECI.vC	2.9%	17.8%	20.1%	48.5%	10.7%	100.0%

GECI.vC * Q15 Crosstabulation

			Q15					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	91	70	121	215	59	556
		% within GECI.vC	16.4%	12.6%	21.8%	38.7%	10.6%	100.0%
	1 - Post	Count	41	32	44	221	62	400
		% within GECI.vC	10.3%	8.0%	11.0%	55.3%	15.5%	100.0%
Total		Count	132	102	165	436	121	956
		% within GECI.vC	13.8%	10.7%	17.3%	45.6%	12.7%	100.0%

GECI.vC * Q16 Crosstabulation

			Q16					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	98	113	61	139	144	555
		% within GECI.vC	17.7%	20.4%	11.0%	25.0%	25.9%	100.0%
	1 - Post	Count	29	45	22	67	237	400
		% within GECI.vC	7.3%	11.3%	5.5%	16.8%	59.3%	100.0%
Total		Count	127	158	83	206	381	955
		% within GECI.vC	13.3%	16.5%	8.7%	21.6%	39.9%	100.0%

GECI.vC * Q17 Crosstabulation

			Q17					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	81	207	104	87	76	555
		% within GECI.vC	14.6%	37.3%	18.7%	15.7%	13.7%	100.0%
	1 - Post	Count	32	253	56	35	23	399
		% within GECI.vC	8.0%	63.4%	14.0%	8.8%	5.8%	100.0%
Total		Count	113	460	160	122	99	954
		% within GECI.vC	11.8%	48.2%	16.8%	12.8%	10.4%	100.0%

GECI.vC * Q18 Crosstabulation

			Q18					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	91	100	153	90	122	556
		% within GECI.vC	16.4%	18.0%	27.5%	16.2%	21.9%	100.0%
	1 - Post	Count	22	66	82	57	172	399
		% within GECI.vC	5.5%	16.5%	20.6%	14.3%	43.1%	100.0%
Total		Count	113	166	235	147	294	955
		% within GECI.vC	11.8%	17.4%	24.6%	15.4%	30.8%	100.0%

GECI.vC * Q19 Crosstabulation

			Q19					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	187	215	93	43	18	556
		% within GECI.vC	33.6%	38.7%	16.7%	7.7%	3.2%	100.0%
	1 - Post	Count	78	206	51	42	23	400
		% within GECI.vC	19.5%	51.5%	12.8%	10.5%	5.8%	100.0%
Total		Count	265	421	144	85	41	956
		% within GECI.vC	27.7%	44.0%	15.1%	8.9%	4.3%	100.0%

GECI.vC * Q20 Crosstabulation

			Q20					Total
			A	B	C	D	E	
GECI.vC	0 - Pre	Count	59	157	195	118	26	555
		% within GECI.vC	10.6%	28.3%	35.1%	21.3%	4.7%	100.0%
	1 - Post	Count	21	242	91	39	6	399
		% within GECI.vC	5.3%	60.7%	22.8%	9.8%	1.5%	100.0%
Total		Count	80	399	286	157	32	954
		% within GECI.vC	8.4%	41.8%	30.0%	16.5%	3.4%	100.0%

APPENDIX O: GREENHOUSE EFFECT CONCEPT INVENTORY, FINAL VERSION

This appendix provides a copy of the final Greenhouse Effect Concept Inventory (GECI), discussed in Section 4.8. As described in this section, Items 8 and 9 may be revised in future publications of the GECI. Interested instructors are encouraged to use the GECI instrument in their courses. It is also requested that results from administration of the GECI be forwarded to John Michael Keller.

Greenhouse Effect Concept Inventory
(GECI)

Do not write on this form.
Use scantron sheet for all answers.

On the scantron sheet, bubble in the best answer for each question. Please do not write on this survey.

1) Which of the following is the most abundant greenhouse gas?
   a) carbon dioxide (CO_2)
   b) water vapor (H_2O)
   c) methane (CH_4)
   d) oxygen (O_2)
   e) ozone (O_3)

2) Earth's atmosphere is warmer than it would be without a greenhouse effect. Which form of energy is absorbed by the atmosphere and mainly causes this increased temperature?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

3) On average, the total amount of energy leaving the Earth system to space
   a) is greater than the amount of energy arriving from space.
   b) is less than the amount of energy arriving from space.
   c) is roughly equal to the amount of energy arriving from space.
   d) depends upon the concentration of greenhouse gases in the atmosphere.
   e) depends upon the status of ozone in the atmosphere.

4) Which of the following is a primary characteristic of greenhouse gases?
   a) They can destroy certain molecules in the atmosphere.
   b) They bend and magnify sunlight entering the atmosphere.
   c) They can trap certain molecules in the atmosphere.
   d) They can bounce around more in the atmosphere.
   e) They are transparent to some forms of energy but not all.

5) The greenhouse effect is a very ______ process probably caused by ______.
   a) recent ; burning of fossil fuels, industry, agriculture, and other human activities.
   b) old ; plants that increase humidity and create conditions similar to those in a greenhouse found at a plant nursery.
   c) recent ; depletion of the ozone layer which allows more ultraviolet sunlight to reach the Earth's surface.
   d) old ; interactions between naturally occurring gases and various forms of energy in the atmosphere.
   e) recent ; natural processes including volcanic emission and changes in solar activity.

6) During the nighttime, Earth's surface mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) Earth's surface does not give off energy during the nighttime

7) Which of the following most strongly affects Earth's overall surface temperature?
   a) heat released by factories and other industrial activities
   b) the destruction of the ozone layer allowing more sunlight into the atmosphere
   c) the flow of different forms of energy through the atmosphere
   d) air pollution trapped in the atmosphere by gases
   e) sunlight being magnified and focused by gases in the atmosphere

8) Which one of the following is <u>not</u> a greenhouse gas?
   a) carbon dioxide (CO_2)
   b) water vapor (H_2O)
   c) methane (CH_4)
   d) oxygen (O_2)
   e) ozone (O_3)

9) Which of the following best describes the relationship between the greenhouse effect and global warming?
   a) The greenhouse effect and global warming are the same thing.
   b) An increase in the greenhouse effect may be causing global warming.
   c) Global warming may be causing an increase in the greenhouse effect.
   d) The greenhouse effect and global warming are likely unrelated.
   e) There is no definite proof that either the greenhouse effect or global warming exist.

10) The Sun mainly gives off (radiates) which two forms of energy?
   a) ultraviolet and x-ray
   b) ultraviolet and infrared
   c) visible and ultraviolet
   d) infrared and visible
   e) radio and infrared

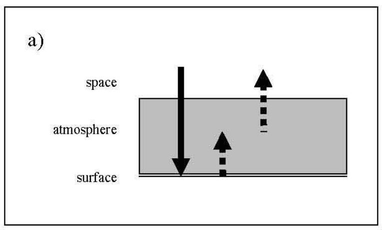
11) A planet that has a greenhouse effect
   a) receives more UV sunlight because it lacks ozone in its atmosphere.
   b) has an atmosphere that absorbs and then gives off certain forms of energy but not all.
   c) receives more energy because it is closer to its central star.
   d) has an altered atmosphere due to living organisms.
   e) does not radiate any energy away into outer space.

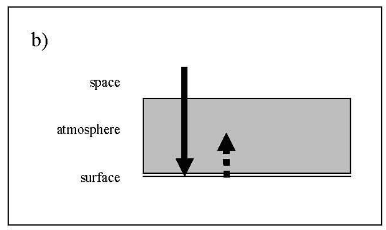
12) Earth's surface is heated mainly by which two forms of energy?
   a) ultraviolet and x-ray
   b) ultraviolet and infrared
   c) visible and ultraviolet
   d) infrared and visible
   e) radio and infrared

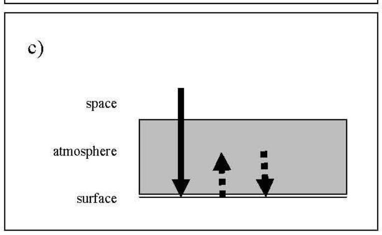
13) If human civilization had never developed on Earth, would there be a greenhouse effect?
   a) Yes, the greenhouse effect is caused by naturally occurring gases in the atmosphere.
   b) Yes, the greenhouse effect is caused by plants giving off gases during photosynthesis.
   c) No, the greenhouse effect is caused by humans burning fossil fuels and releasing pollutants.
   d) No, the greenhouse effect is caused by humans depleting ozone in the atmosphere.
   e) No, there is no conclusive evidence that a greenhouse effect exists.

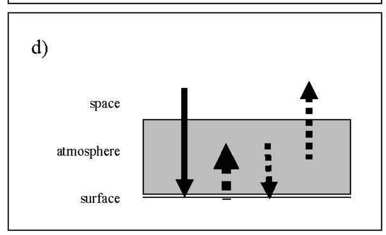
14) At which of the following does the Sun give off (radiate) energy at its maximum intensity?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) x-ray

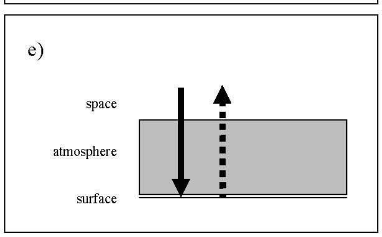
15) Each diagram below shows Earth's surface, the atmosphere, and outer space. The solid arrow represents incoming energy from the Sun that is absorbed by the surface. The dashed arrow represents energy that is radiated or given off by the surface and atmosphere. The thickness of the arrow roughly represents the amount of energy. Select the diagram that best represents the transport of energy among Earth's surface, the atmosphere, and outer space.











16) Which of the following are the two most abundant greenhouse gases in Earth's atmosphere?
   a) carbon dioxide (CO_2) and methane (CH_4)
   b) ozone (O_3) and carbon dioxide (CO_2)
   c) nitrogen (N_2) and oxygen (O_2)
   d) oxygen (O_2) and carbon dioxide (CO_2)
   e) water vapor (H_2O) and carbon dioxide (CO_2)

17) Earth's atmosphere mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) Earth's atmosphere does not give off energy

18) Due to the greenhouse effect, Earth's overall surface temperature is affected primarily by
   a) an increase in energy entering from space.
   b) a decrease in energy leaving to space.
   c) both an increase in energy entering from and a decrease in energy leaving to space.
   d) energy being permanently trapped in the atmosphere.
   e) an increase in the amount of energy exchanged between the surface and atmosphere.

19) You walk from a region of shade into a region of direct sunlight and notice you start to feel warmer. Which of the following most correctly describes the cause of the temperature increase?
   a) You absorb more ultraviolet energy than you give off (radiate) as visible energy.
   b) You absorb more visible energy than you give off (radiate) as infrared energy.
   c) You reflect more ultraviolet energy than you give off (radiate) as infrared energy.
   d) You reflect more visible energy than you give off (radiate) as infrared energy.
   e) You reflect more infrared energy than you give off (radiate) as visible energy.

20) During the daytime, Earth's surface mainly gives off (radiates) which form of energy?
   a) radio
   b) infrared
   c) visible
   d) ultraviolet
   e) Earth's surface does not give off energy during the daytime

21) What is your gender?
   a) Male
   b) Female

22) What year are you in university?
   a) Freshman
   b) Sophomore
   c) Junior
   d) Senior
   e) Other

23) Which of the following best characterizes your academic major(s)?
   a) Science
   b) Non-science
   c) Double major (science and non-science)
   d) Other

24) Prior to this semester, which of the following best describes your previous coursework?
   a) I have never taken a class that covers the greenhouse effect.
   b) Before college, I took a class that briefly touched upon the greenhouse effect.
   c) Before college, I took a class that dealt extensively with the greenhouse effect.
   d) In college, I took a class that briefly touched upon the greenhouse effect.
   e) In college, I took a class that dealt extensively with the greenhouse effect.

25) Have any of your other courses besides this course covered the greenhouse effect during this semester?
   a) Yes
   b) No

Thank you for your participation.
Please wait for instructions on returning survey.

APPENDIX P: INSTITUTIONAL REVIEW BOARD APPROVAL MATERIALS

This appendix provides copies of approval letters from the University of Arizona Institutional Review Board (IRB) in the Human Subjects Protection Program. Copies of approved (stamped) Subject's Disclaimer forms (used with SSR and GECI surveys) and the Subject's Consent forms (used with student interviews and GECI.vC interventions) are also provided. These documents include the following:

a. SSR.vA and SSR.vB Approval Letter, dated 30 September 2004
b. SSR.vC and GECI.vA Approval Letter, dated 20 January 2005
c. SSR.vC and GECI.vA Subject's Disclaimer, dated 20 January 2005
d. GECI.vB Approval Letter, dated 19 August 2005
e. GECI.vB Subject's Disclaimer, dated 19 August 2005
f. GECI.vB Addendum Letter, dated 30 August 2005
g. Interview Approval Letter, dated 6 September 2005
h. Interview Subject's Consent, dated 6 September 2005
i. Interview Addendum Letter, dated 7 October 2005
j. GECI..vC Approval Letter, dated 1 February 2006
k. GECI.vC Subject's Disclaimer, dated 1 February 2006
l. GECI.vC Subject's Consent, dated 1 February 2006

Human Subjects Protection Program
http://www.irb.arizona.edu

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(520) 626-6721

30 September 2004

John Keller, M.A., M.S.
Advisor: Ed Prather, Ph.D.
Department of Planetary Sciences
PO Box 210092

RE: PRELIMINARY SURVEY OF STUDENT MISCONCEPTIONS REGARDING THE GREENHOUSE EFFECT

Dear Mr. Keller:

We received documents concerning your above cited project. Regulations published by the U.S. Department of Health and Human Services [45 CFR Part 46.101(b) (4)] exempt this type of research from review by our Institutional Review Board.

Exempt status is granted with the understanding that no further changes or additions will be made to the procedures followed without the review and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Thank you for informing us of your work. If you have any questions concerning the above, please contact this office.

Sincerely,

Rebecca Dahl

Rebecca Dahl, R.N., Ph.D.
Director
Human Subjects Protection Program

cc: Departmental/College Review Committee

Human Subjects Protection Program
http://www.irb.arizona.edu

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(520) 626-6721

20 January 2005

John Keller, Ph.D. Candidate
Advisor: Ed Prather, Ph.D.
Department of Planetary Science
Lunar and Planetary Lab
1629 E. University Blvd.
PO Box 210092

RE: ELICITING STUDENTS' BELIEFS ABOUT THE GREENHOUSE EFFECT

Dear Mr. Keller:

We received documents concerning your above cited project. Regulations published by the U.S. Department of Health and Human Services [45 CFR Part 46.101(b) (2)] exempt this type of research from review by our Institutional Review Board. **Note: A copy of your disclaimer form, with IRB approval stamp affixed, is enclosed for duplication and use in enrolling subjects.**

Please be advised that **clearance from academic and/or other official authorities for site(s) where proposed research is to be conducted must be obtained prior to performance of this study. Evidence of this must be submitted to the Human Subjects Protection Program office.**

Exempt status is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consenting instrument used (copies of which we have on file) without the review and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Thank you for informing us of your work. If you have any questions concerning the above, please contact this office.

Sincerely,

Rebecca Dahl

Rebecca Dahl, R.N., Ph.D.
Director
Human Subjects Protection Program

cc: Departmental/College Review Committee

SUBJECT'S DISCLAIMER
GREENHOUSE EFFECT SURVEY

Title of Project: Eliciting Students' Beliefs about the Greenhouse Effect

You are being invited to voluntarily participate in the above-titled research study. The purpose of the study is 1) to identify and characterize student understanding of the greenhouse effect and 2) to assess instructional strategies for teaching this topic. You are eligible to participate because you are at least 18 years of age and are enrolled in a general education science course.

If you agree to participate, your participation will involve responding to the questions on the attached survey. You may choose not to answer some or all of the questions. Your name will be removed from this survey after a code number has been randomly assigned to your response. A spreadsheet connecting your name and the code number will be maintained throughout the semester in order to assign the same code number on a later administration of this survey near the end of the course. Only the principal investigator, John M. Keller, Ph.D. candidate, will have access to this spreadsheet. After both surveys have been coded, the spreadsheet will be destroyed. Your responses to this survey will in no way impact your grade.

Any questions you have will be answered and you may withdraw from the study at any time. There are no known risks from your participation and no direct benefit from your participation is expected. There is no cost to you except for your time and you will not be compensated for your participation.

Only the principal investigator and John M. Keller, Ph.D. candidate, will have access to the information that you provide. In order to maintain your confidentiality, your name will not be revealed in any reports that result from this project.

You can obtain further information from the principal investigator, John M. Keller, Ph.D. candidate, at (520) 621-1632. If you have questions concerning your rights as a research subject, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-6721.

By participating in this study, you are giving permission for the investigator to use your information for research purposes.

Thank you.

John M. Keller, PhD. Candidate

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19 August 2005

John Keller, Ph.D. Candidate
Advisor: Ed Prather, Ph.D.
Department of Planetary Science
Lunar and Planetary Lab
1629 E. University Blvd.
PO Box 210092

RE: ELICITING STUDENTS' BELIEFS ABOUT THE GREENHOUSE EFFECT

Dear Mr. Keller:

We received your 15 August 2005 letter and accompanying revised survey instruments and disclaimer form for the above cited project. Changes include addition of study participants (n=2000), expansion of recruitment sites to include introductory science courses for undergraduate science majors, revised surveys (minor administrative modifications to clarify and simplify surveys, consolidation of questions, removal of open-ended questions and use of scantron sheets for survey administration), revision of the code linking surveys (will now use month, day of birth and last three letters of the middle name rather than random assignment of a code number), expanded instructions to participants explaining the revised coding system and removal of participant compensation. Approval for these changes to your exempt project effective 19 August 2005. **Note: A copy of your disclaimer form, with IRB approval stamp affixed, is enclosed for duplication and use in enrolling subjects.**

Please be advised that **clearance from academic and/or other official authorities for site(s) where proposed research is to be conducted must be obtained prior to performance of this study. Evidence of this must be submitted to the Human Subjects Protection Program office.**

Exempt status is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consenting instrument used (copies of which we have on file) without the review and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Thank you for informing us of your work. If you have any questions concerning the above, please contact this office.

Sincerely,

Rebecca Dahl, R.N., Ph.D.
Director
Human Subjects Protection Program

cc: Departmental/College Review Committee

SUBJECT'S DISCLAIMER
GREENHOUSE EFFECT SURVEY

Title of Project: Eliciting Students' Beliefs about the Greenhouse Effect

You are being invited to voluntarily participate in the above-titled research study. The purpose of the study is 1) to identify and characterize student understanding of the greenhouse effect and 2) to assess instructional strategies for teaching this topic. You are eligible to participate because you are at least 18 years of age and are enrolled in this science course.

If you agree to participate, your participation will involve responding to the questions on the attached survey. You may choose not to answer some or all of the questions. To maintain anonymity and to link surveys from the beginning and end of the semester, you will be asked to create an encrypted code to identify your survey. This code will involve the month and day of your birthday along with the last three letters of your middle name. Your responses to this survey will in no way impact your grade.

Any questions you have will be answered and you may withdraw from the study at any time. There are no known risks from your participation and no direct benefit from your participation is expected. There is no cost to you except for your time and you will not be compensated for your participation.

Only the principal investigator and John M. Keller, Ph.D. candidate, will have access to the information that you provide. In order to maintain your confidentiality, your identity will not be revealed in any reports that result from this project.

You can obtain further information from the principal investigator, John M. Keller, Ph.D. candidate, at (520) 621-1632. If you have questions concerning your rights as a research subject, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-6721.

By participating in the questions on the survey, you are giving permission for the investigator to use your information for research purposes.

Thank you.

John M. Keller

John M. Keller, PhD. Candidate

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30 August 2005

John Keller, Ph.D. Candidate
Advisor: Ed Prather, Ph.D.
Department of Planetary Science
Lunar and Planetary Lab
1629 E. University Blvd.
PO Box 210092

RE: ELICITING STUDENTS' BELIEFS ABOUT THE GREENHOUSE EFFECT

Dear Mr. Keller:

We received your 23 August 2005 letter for the above referenced project. Change includes addition of study participants (n=2,500). Approval for this change to your exempt project effective 30 August 2005.

Please be advised that **clearance from academic and/or other official authorities for site(s) where proposed research is to be conducted must be obtained prior to performance of this study. Evidence of this must be submitted to the Human Subjects Protection Program office.**

Exempt status is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consenting instrument used (copies of which we have on file) without the review and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Thank you for informing us of your work. If you have any questions concerning the above, please contact this office.

Sincerely,

Rebecca Dahl, R.N., Ph.D.
Director
Human Subjects Protection Program

cc: Departmental/College Review Committee

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6 September 2005

John Keller, M.S.
Advisor: Ed Prather, Ph.D.
Department of Planetary Science
1629 E. University Blvd.
Tucson, AZ 85721

RE: BSC B05.204 STUDENT INTERVIEWS REGARDING UNDERSTANDING OF THE GREENHOUSE EFFECT

Dear Mr. Keller:

We received your research proposal as cited above. The procedures to be followed in this study pose no more than minimal risk to participating subjects and have been reviewed by the Institutional Review Board (IRB) through an Expedited Review procedure as cited in the regulations issued by the U.S. Department of Health and Human Services [45 CFR Part 46.110(b)(1)] based on their inclusion under research categories 6 and 7. As this is not a treatment intervention study, the IRB has waived the statement of Alternative Treatments in the consent form as allowed by 45 CFR 46.116(d). Although full Committee review is not required, a brief summary of the project procedures is submitted to the Committee for their endorsement and/or comment, if any, after administrative approval is granted. This project is approved with an **expiration date of 6 September 2006.** Please make copies of the attached IRB stamped consent documents to consent your subjects.

The Human Subjects Committee (Institutional Review Board) of the University of Arizona has a current Federal Wide Assurance of compliance, number FWA00004218, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consent form(s) used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

A university policy requires that all signed subject consent forms be kept in a permanent file in an area designated for that purpose by the Department Head or comparable authority. This will assure their accessibility in the event that university officials require the information and the principal investigator is unavailable for some reason.

Sincerely yours,

Theodore J Glattke, Ph.D.
Chair, Social and Behavioral Sciences Human Subjects Committee

TJG:pm

cc: Departmental/College Review Committee

SUBJECT'S CONSENT FORM

Student Interviews Regarding Understanding of the Greenhouse Effect

Principal Investigator: John M. Keller, PhD. Candidate
Department of Teaching Planetary Sciences, 1629 E. University Blvd, Tucson, AZ 85721

I AM BEING ASKED TO READ THE FOLLOWING MATERIAL TO ENSURE THAT I AM INFORMED OF THE NATURE OF THIS RESEARCH STUDY AND OF HOW I WILL PARTICIPATE IN IT, IF I CONSENT TO DO SO. SIGNING THIS FORM WILL INDICATE THAT I HAVE BEEN SO INFORMED AND THAT I GIVE MY CONSENT. FEDERAL REGULATIONS REQUIRE WRITTEN INFORMED CONSENT PRIOR TO PARTICIPATION IN THIS RESEARCH STUDY SO THAT I CAN KNOW THE NATURE AND RISKS OF MY PARTICIPATION AND CAN DECIDE TO PARTICIPATE OR NOT PARTICIPATE IN A FREE AND INFORMED MANNER.

PURPOSE
I am being invited to participate voluntarily in the above-titled research project. The purpose of this project is to explore what undergraduate students understand regarding the topic of the Greenhouse Effect.

SELECTION CRITERIA
I am being invited to participate because I am a student in a general education requirement science course (i.e., a Natural Science, NATS, course) and I am 18 years of age or older. I have been selected because I expressed a willingness to participate in the interview when this research project was described to our class. Approximately 12-20 subjects will be enrolled in this portion of the study.

PROCEDURE(S)
If I agree to participate, I will be asked to consent to the following: one formal interview, lasting between 30 and 60 minutes. The interview will take place on the University of Arizona campus in the Kuiper Space Science building in Room 301 or 309, at a mutually agreeable time. I will first be asked to provide answers to various questions that I have already seen on the Greenhouse Effect survey I completed earlier this semester. We will then discuss my reasoning behind these answers as well as additional questions regarding my understanding of the greenhouse effect and flow of energy through Earth's atmosphere. The interview will be audio taped.

RISKS
There are no known risks. Participation or not in this interview will have no impact on my grade.

BENEFITS
No direct benefit can be guaranteed. It is possible that I will more deeply consider my understanding of topics than I had done previously, and as a result may or may not come to a more complete or scientifically accurate understanding of the topics.

CONFIDENTIALITY
All information I provide for this study will be kept anonymous and treated with the highest degree of confidentiality. Audiotapes will be made available only to the Principal Investigator, John M. Keller, PhD Candidate. Information on all transcripts and field notes will be identified only by an initial or a pseudonym of my choosing. The final product of this study will be a scholarly paper written in partial fulfillment of the requirements for the degree of Doctor of Philosophy. Additional products may include a published paper. In the event that transcript excerpts are used in the final report, my name will not be used, and additional information will be disguised or suppressed to hide my identity.

PARTICIPATION COSTS AND SUBJECT COMPENSATION
There are no costs involved in this study except a maximum of 60 minutes of my time. There is no compensation of any kind to participants. The researcher will receive no monetary compensation for conducting the study.

CONTACTS
I can obtain further information from the Principal Investigator, **John M. Keller, PhD candidate,** at **(520) 621-1632**. If I have questions concerning my rights as a research subject, I may call the Human Subjects Protection Program office at (520) 626-6721.

AUTHORIZATION
BEFORE GIVING MY CONSENT BY SIGNING THIS FORM, THE METHODS, INCONVENIENCES, RISKS, AND BENEFITS HAVE BEEN EXPLAINED TO ME AND MY QUESTIONS HAVE BEEN ANSWERED. I MAY ASK QUESTIONS AT ANY TIME AND I AM FREE TO WITHDRAW FROM THE PROJECT AT ANY TIME WITHOUT CAUSING BAD FEELINGS. MY PARTICIPATION IN THIS PROJECT MAY BE ENDED BY THE INVESTIGATOR FOR REASONS THAT WOULD BE EXPLAINED. NEW INFORMATION DEVELOPED DURING THE COURSE OF THIS STUDY WHICH MAY AFFECT MY WILLINGNESS TO CONTINUE IN THIS RESEARCH PROJECT WILL BE GIVEN TO ME AS IT BECOMES AVAILABLE. THIS CONSENT FORM WILL BE FILED IN AN AREA DESIGNATED BY THE HUMAN SUBJECTS COMMITTEE WITH ACCESS RESTRICTED TO THE PRINCIPAL INVESTIGATOR, JOHN M. KELLER OR AUTHORIZED REPRESENTATIVE OF THE PLANETARY SCIENCE DEPARTMENT. I DO NOT GIVE UP ANY OF MY LEGAL RIGHTS BY SIGNING THIS FORM. A COPY OF THIS SIGNED CONSENT FORM WILL BE GIVEN TO ME.

______________________________ ______________________

Subject's Signature Date

____

Type or PRINT Full Name

INVESTIGATOR'S AFFIDAVIT

I or my designee have carefully explained to the subject the nature of the above project. I or my designee hereby certify that to the best of my knowledge the person who is signing this consent form understands clearly the nature, demands, benefits, and risks involved in his/her participation and his/her signature is legally valid. A medical problem or language or educational barrier has not precluded this understanding.

______________________________ _________________________

Signature of Investigator Date

______________________________ _________________________

Signature of Presenter Date

1/2000

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7 October 2005

John Keller, M.S.
Advisor: Ed Prather, Ph.D.
Department of Planetary Science
1629 E University Blvd.
Tucson, AZ 85721

RE: **BSC 05.204** STUDENT INTERVIEWS REGARDING UNDERSTANDING OF THE GREENHOUSE EFFECT

Dear Mr. Keller:

We received your 28 September 2005 letter above referenced project. Permission is requested to:

- add a follow-up interview for interested students who volunteered for pre-instruction surveys. The structure and format of the follow-up interview will be the same as the initial interview.

These changes do not impact subject safety. Approval of these changes is granted effective 5 October 2005.

The Human Subjects Committee (Institutional Review Board) of the University of Arizona has a current ***Federal Wide Assurance*** of compliance, number ***FWA00004218***, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consent form(s) used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Sincerely yours,

Theodore J. Glattke, Ph.D.
Chair, Social and Behavioral Sciences Human Subjects Committee

TJG:md

cc: Departmental/College Review Committee

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1 February 2006

John Keller, Ph.D. Candidate
Advisor: Edward Prather, Ph.D.
Department of Planetary Science
Lunar and Planetary Lab
PO Box 210092

RE: **BSC B06.31** TESTING IMPACT OF LECTURE TUTORIAL ACTIVITY ON STUDENTS UNDERSTANDING OF THE GREENHOUSE EFFECT

Dear Mr. Keller:

We received your research proposal as cited above. The procedures to be followed in this study pose no more than minimal risk to participating subjects and have been reviewed by the Institutional Review Board (IRB) through an Expedited Review procedure as cited in the regulations issued by the U.S. Department of Health and Human Services [45 CFR Part 46.110(b)(1)] based on their inclusion under research category 7 (research on individual/group characteristics). Although full Committee review is not required, a brief summary of the project procedures is submitted to the Committee for their endorsement and/or comment, if any, after administrative approval is granted. This project is approved effective **1 February 2006** for a period of one year.

The Human Subjects Committee (Institutional Review Board) of the University of Arizona has a current ***Federalwide Assurance*** of compliance, ***FWA00004218***, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consent form(s) used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and you College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Sincerely yours,

Theodore Glattke

Theodore Glattke, Ph.D.
Chairman
Social Behavioral Sciences Human Subjects Committee

TG:rd

cc: Departmental/College Review Committee

SUBJECT'S DISCLAIMER
GREENHOUSE EFFECT SURVEY

Title of Project: Student Understanding of the Greenhouse Effect

You are being invited to voluntarily participate in the above-titled research study. The purpose of the study is 1) to identify and characterize student understanding of the greenhouse effect and 2) to assess an instructional activity regarding the greenhouse effect.. You are eligible to participate because you are at least 18 years of age and are enrolled in this science course.

If you agree to participate, your participation will involve responding to the questions on the attached survey. You may choose not to answer some or all of the questions. To maintain anonymity and to link surveys from the beginning and end of the semester, you will be asked to provide your initials and birthdate to identify your survey. Your responses to this survey will in no way impact your grade.

Later in the semester, students in selected classes will be asked to voluntarily complete an additional instructional activity regarding the greenhouse effect. These students will be informed of their opportunities to volunteer for this part of the study. Finally, a post instructional survey will be administered at the end of the semester.

Any questions you have regarding this research project will be answered and you may withdraw from the study at any time. There are no known risks from your participation and no direct benefit from your participation is expected. There is no cost to you except for your time and you will not be compensated for your participation.

Only the principal investigator and John M. Keller, Ph.D. candidate, will have access to the information that you provide. In order to maintain your confidentiality, your identity will not be revealed in any reports that result from this project.

You can obtain further information from the principal investigator, John M. Keller, Ph.D. candidate, at (520) 621-1632. If you have questions concerning your rights as a research subject, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-6721.

By participating in the questions on the survey, you are giving permission for the investigator to use your information for research purposes.

Thank you.

John M. Keller, PhD. Candidate

APPROVED BY UNIVERSITY OF AZ IRB
THIS STAMP MUST APPEAR ON ALL
DOCUMENTS USED TO CONSENT SUBJECTS.
DATE: 2/01/06 EXPIRATION: 2/01/07

SUBJECT'S CONSENT FORM

Project Title: Student Understanding of the Greenhouse Effect

You are being asked to read the following material to ensure that you are informed of the nature of this research study and of how you will participate in it, if you consent to do so. Signing this form will indicate that you have been so informed and that you give your consent. Federal regulations require written informed consent prior to participation in this research study so that you can know the nature and risks of your participation and can decide to participate or not participate in a free and informed manner.

PURPOSE

You are being invited to participate voluntarily in the above-titled research project. The purpose of this project is determine whether the use of an in-class activity regarding the greenhouse effect can increase student understanding of this concept.

SELECTION CRITERIA

The Principal Investigator or a member of his study staff will discuss the requirements for participation in this study with you. To be eligible to participate, you must be age 18 or older and a student enrolled in this course that is being given the opportunity to complete this instructional activity. A total of 1200 individuals will be enrolled in this study locally.

ALTERNATIVE TREATMENT(S)

This is not a treatment study.

PROCEDURE(S)

The following information describes your participation in this study that will last up to one class period:

- At the beginning of the semester, you may have voluntarily completed a pre-instructional survey regarding the greenhouse effect. This survey took roughly 10-15 minutes to complete.
- The attached activity will take roughly 30-40 minutes to complete. In the activity, you will work in a group with 3-4 students to discuss and answer roughly 20 questions about the important concepts related to the greenhouse effect and flow of energy through the atmosphere.
- During the last month of the semester, you will be asked to voluntarily complete a post-instructional survey during class. This survey will take roughly 10-15 minutes to complete

RISKS

There are no known risks. Participation in this interview will have no impact on your grade.

BENEFITS

There is no direct benefit to you from your participation. It is possible that you will more deeply consider your understanding of topics than you have done previously, and as a result may or may not come to a more complete or scientifically accurate understanding of the topics.

CONFIDENTIALITY
Your confidentiality will be ensured through the use of a code involving your initials and birthdate that will be used to link your pre- and post-instructional surveys to your responses on this activity. After these documents have been linked, your initials and birthdates will be removed from documents and destroyed.

PARTICIPATION COSTS AND SUBJECT COMPENSATION
There is no cost to you for participating except your time, approximately 40 minutes for the activity and 10-15 minutes for the post-instructional survey. You will not be compensated for your participation.

CONTACTS
You can obtain further information from the principal investigator John M Keller, Ph.D. Candidate, at (520)621-1632. If you have questions concerning your rights as a research subject, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-6721. (If out of state use the toll-free number 1-866-278-1455.)

AUTHORIZATION
Before giving my consent by signing this form, the methods, inconveniences, risks, and benefits have been explained to me and my questions have been answered. I may ask questions at any time and I am free to withdraw from the project at any time without causing bad feelings or affecting my medical care. My participation in this project may be ended by the investigator or by the sponsor for reasons that would be explained. New information developed during the course of this study which may affect my willingness to continue in this research project will be given to me as it becomes available. This consent form will be filed in an area designated by the Human Subjects Committee with access restricted by the principal investigator, John Keller, Ph.D. Candidate, or authorized representative of the University of Arizona Planetary Science Department. I do not give up any of my legal rights by signing this form. A copy of this signed consent form will be given to me.

____________________________ ________________________
Subject's Signature Date

INVESTIGATOR'S AFFIDAVIT:
Either I have or my agent has carefully explained to the subject the nature of the above project. I hereby certify that to the best of my knowledge the person who signed this consent form was informed of the nature, demands, benefits, and risks involved in his/her participation.

[signature] 2/24/06

Signature of Presenter Date

_______________________ 2/28/06

Signature of Investigator Date

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