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Laboratory Experiment

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A Simple, Student-Built Spectrometer To Explore Infrared Radiation and Greenhouse Gases

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S *Supporting Information*

ABSTRACT: In this experiment, students build a spectrometer to explore infrared radiation and greenhouse gases in an inquiry-based investigation to introduce climate science in a general chemistry lab course. The lab is based on the exploration of the thermal effects of molecular absorption of infrared radiation by greenhouse and non-greenhouse gases. A novel feature of the experiment has students building an infrared spectrometer, using a hot plate as an IR source, a sample compartment employing a plastic cuvette holder with open sides (to standardize the path length), and a low-cost infrared thermometer. Students, working in groups, (1) explore a PhET simulation; (2) design a set of experiments in response to a scientific question, "comparing the absorption of infrared light in the presence and absence of each different sample of gas, are there any significant differences that can be observed experimentally?"; (3) reflect on climate science and their experimental results by visiting the American Chemical Society Climate Science Toolkit; and (4) communicate their results in lab by constructing and presenting a poster. Assessment of student responses to a pre- and postexperiment question suggests that the lab has a positive influence on student understanding of the concepts involved in identifying greenhouse gases. Results from postexperiment questions also provide information for what aspects of the online resources students found useful.

KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Environmental Chemistry, Laboratory Instruction, Collaborative/Cooperative Learning, Hands-On Learning/Manipulatives, Inquiry-Based/Discovery Learning, Internet/Web-Based Learning, Problem Solving/Decision Making, Laboratory Equipment/Apparatus*

INTRODUCTION

A recent poll published in 2015 by the PEW Research Center[1] reveals significant gaps between the public's and scientists' perceptions involving climate science. For example, only 50% of the general public agreed that climate change is mostly caused by human activity, while for AAAS scientists, agreement is much higher (87%).[1] It has been suggested that these differences originate from different understandings of scientific terms in the public and scientific communities.[2] It has also been suggested that telling "both sides" of the climate change story may lead to a form of "informational bias".[3] Entering, college-level students are not immune to these issues, and it is reasonable to suppose that they would hold some of the common misconceptions associated with the greenhouse effect.[4]

Given the impact of carbon dioxide and other small molecules on the greenhouse effect and climate change, it is understandable that authors have steadily reported *in this Journal* on this significant topic. A "thematic" course on the chemistry and controversy of climate change for upper-level non-STEM students has recently been developed,[5] a tested classroom demonstration to illustrate the greenhouse effect is available,[6] and integrated lab-lecture case studies for nonscience majors have been developed.[7] There has also been a significant number of laboratory experiments developed to understand absorption of infrared radiation by small molecules,[8] carbon dioxide absorption of infrared radiated by the earth,[9] the use of photoacoustics to confirm the infrared absorption by greenhouse gases,[10] the use of calorimetry to explore heat retention and global warming,[11] and an experiment that uses vibrational spectroscopy and a simple spreadsheet analysis to estimate the greenhouse warming potentials of greenhouse gases.[12] Finally, a study to investigate general chemistry students' understanding of the chemistry underlying climate change was recently reported.[13]

While climate science is sometimes portrayed as controversial in the press, the mechanism whereby absorption of infrared radiation by gases increases temperature is not controversial at all. We reasoned, therefore, that designing an experiment to focus on this mechanism would help to provide students with a sound foundation for further understanding of climate science. The resulting lab experiment, "Building a Spectrometer To Explore Infrared Radiation and Greenhouse Gases" allows students to (1) design their own experiments to generate quantitative data that can be used to identify the relative absorption properties of various gases, (2) interpret

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these results with the help of a molecular-scale, mechanistic PhET simulation, (3) reflect on climate science and their experimental results by visiting the American Chemical Society Climate Science Toolkit, and (4) communicate these findings as part of a poster presentation. Students complete the experiment during a 3 h lab session, working in groups of three or four. A representation of three activities that students engage in during this experiment is shown in Figure 1.

Figure 1. Representation of three activities that students engage in during lab. Logos from PhET and Climate Science Toolkit are used with permission from PhET Interactive Simulations, University of Colorado Boulder, http://phet.colorado.edu, and the American Chemical Society, http://www.acs.org/content/acs/en/climatescience.html, respectively.

The goals of the lab are as follows:

(1) to make students aware of climate science online resources;
(2) to provide information and tools such that students can identify atmospheric greenhouse gases; and
(3) to allow students to communicate scientific results to their peers.

Assessment data consist of students' responses to pre- and postexperiment questions about their understanding of the concepts involved in identifying greenhouse gases and postexperiment questions about what aspects of the online resources students found useful. Student responses were also examined to gather preliminary data regarding the occurrences of some common misconceptions about the mechanism underlying the greenhouse effect and the role of atmospheric gases in this process.

■ BACKGROUND

The US EPA defines greenhouse gases as "gases that trap heat in the atmosphere."[14] This definition is scientifically limited because it does not explain the source of heat or the molecular-scale mechanisms that occur in the atmosphere that cause heat to be trapped. Interactions of atmospheric gases with electromagnetic radiation are not easily observable and therefore can be inherently difficult to understand. Surveys of the general public have shown that very few people, even college graduates, can explain the mechanism behind the greenhouse effect.[15,16] Students easily form misconceptions about the greenhouse effect if they have an incomplete understanding of microscale atmospheric interactions,[13] and/or confusion about various climate change concepts.[17,18]

A host of misconceptions about the greenhouse effect held by secondary students, undergraduates, and the general public have been documented.[4,15,16,19−25] One common misconception held by learners of various ages is that the greenhouse effect and consequent atmospheric warming is linked to depletion of the Earth's ozone layer.[20−23] Some people conceive that extra sunlight coming through the "hole" in the ozone layer heats up the planet. Additionally, some think that the ozone layer is a barrier that traps radiation in the atmosphere. A similar misunderstanding held by many is that greenhouse gases form a physical barrier, like a "blanket" in the atmosphere, which traps heat by physically blocking energy transfer.[13,21−23] Other documented misconceptions include conflations with physical properties of agricultural greenhouses and beliefs that atmospheric gases intensify incoming radiation.[22,23]

To understand how greenhouse gases trap heat in the atmosphere, it is first necessary to realize that there is no macroscale physical barrier involved. Instead, energy transfer processes happen at the molecular scale, when certain tropospheric gas molecules, called greenhouse gases, absorb electromagnetic radiation. The structure of greenhouse gas molecules is such that their interaction with infrared (IR) radiation induces molecular motions (translations, rotations, and vibrations).[26] Greenhouse gas molecules absorb only IR radiation, so to understand the mechanisms of atmospheric warming students must distinguish the heat source as long-wave (IR) radiation coming from the Earth, as opposed to short-wave ultraviolet (UV) radiation from the sun.

The "Building a Spectrometer To Explore Infrared Radiation and Greenhouse Gases" lab experiment provides a variety of opportunities for students to build better understandings of the fundamental atmospheric chemistry concepts involved in the greenhouse effect and to move beyond common misconceptions. These opportunities are created by allowing students to explore atomic-scale simulations, design their own bench-scale experiment to compare the temperature effects of various gases, consult an authoritative resource on the topic, and analyze, interpret, and communicate experimental results based on their research.

■ EXPERIMENTAL PROCEDURES

The sequential four-part lab experiment allows students to gather scientific information and experimental data and then use scientific reasoning to develop and support a claim about the effects of increasing concentrations of greenhouse gases in the atmosphere. The details of the procedure can be found in Supporting Information Lab Procedures (pdf and zip).

Part 1: Students first explore a PhET simulation to prime their thinking at the atomic scale concerning energy transfer between radiation and various gas molecules. The simulation allows them to explore and visualize the interactions of molecules with IR radiation (and other wavelengths) and observe how the structure of the molecules influences these interactions.

Part 2: Students construct and use a home-built IR spectrometer (see Figure 2) to measure the absorbance of IR radiation by gases. Students work in groups of four to develop an experimental procedure that enables them to record temperature as a function of IR interaction with CO_2 and N_2

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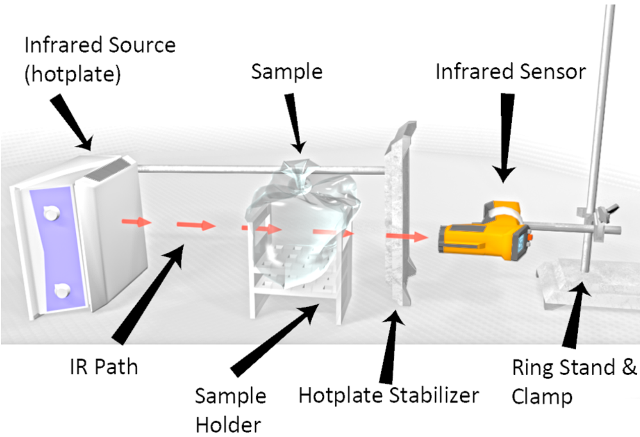

Figure 2. Infrared spectrometer setup used in the Infrared Radiation and Greenhouse Gases lab.

gases. The lab procedure provides instructions for using the IR sensor to record temperatures:

> *"To make measurements, one student holds down the IR thermometer trigger for 10−15 seconds to stabilize the detector before measurements can be made. Another student can place the sample in the sample compartment, gently holding down the bag, while another student can record the temperature of a blank measurement (nothing in the compartment) or a sample in the compartment."*

Students are then asked to design experiments to explore the following question: "Comparing the absorption of infrared light in the presence and absence of each different sample of gas, are there any significant differences that can be observed experimentally?" Student experimental procedures typically include measuring the temperature of an uninflated bag in the sample holder to account for the effect of the plastic bag; then they measure a bag inflated with CO_2; followed by a bag with N_2. Typically, students make five replicate measurements of each sample (blank, CO_2, and N_2) and then do a blank correction to find ΔT ($\Delta T = T_{blank} - T_{sample}$). They can then calculate the mean temperature and standard deviation for each type of sample and compare the ΔT values for each gas. A common variation of this procedure is to alternate measurements between CO_2 and N_2, obtaining a blank measure after each set. An example of the data is shown in Table 1.

Part 3: After gathering experimental data, students are directed to the ACS Climate Science Toolkit Web site, an authoritative source of information about the science of Earth's climate system. From this resource, they can explore valid information about greenhouse gases and the atmospheric greenhouse effect to supplement and make connections with what they have learned from parts 1 and 2 of the lab procedure.

Part 4: Each team of students prepares a poster to communicate their results to their peers. The groups are instructed to use evidence collected using the IR spectrometer, PhET simulation, and ACS climate science toolkit to answer the following question: "How do you think increasing the concentration of CO_2 in the atmosphere would affect the amount of infrared light present in the atmosphere?" Teams summarize their answer, present their reasoning, and then discuss their posters with the class in a 5 min presentation.

Students present their data in poster format in this lab for two reasons. Climate change is a highly relevant topic in society, and many students are interested in talking about this issue. Poster presentations provide students with a great opportunity to practice communicating with their peers about the *science* in climate science. The second reason is that many of the students in our program are science and engineering majors and benefit from opportunities to practice and develop their oral communication skills with this common research presentation format.

HAZARDS

The spectrometer uses a laboratory hot plate as a heat source, and a laser-guided IR detector. Safety precautions for these items are stated in the lab procedure. Precautions should be taken to ensure that the hot plate is placed on a nonflammable surface and an appropriate notice is posted to warn students of this potential hazard. Safety precautions should be a prominent discussion point in the prelab discussion. Use of compressed carbon dioxide and nitrogen gas tanks for the experimental gases requires appropriate safe handling of gases under pressure. Flammable gases should not be used.

DEVELOPMENT CONTEXT

This lab experiment was developed as part of an ongoing effort to reform the laboratory curriculum in the undergraduate introductory general chemistry courses at the University of Maine, a small research-intensive (RU/H, Land and Sea Grant) institution. We have recently developed a new laboratory learning cycle, called **CORE** (**C**hemical **O**bservations, **R**epresentation, **E**xperimentation) which is designed to model productive chemical inquiry and to promote a deeper understanding about the chemistry operating of submicroscopic level.[27]

The "Building a Spectrometer To Explore Infrared Radiation and Greenhouse Gases" experiment was developed in response to the American Chemical Society Presidential Climate Science Challenge Grant program announced by then ACS President

Table 1. Example Student Data from the Building a Spectrometer To Explore Infrared Radiation and Greenhouse Gases Experiment

Measurement	T(Empty Bag) (°C)	$T(CO_2)$ (°C)	$\Delta T(CO_2)$ (°C)	T(Empty Bag) (°C)	$T(N_2)$ (°C)	$\Delta T(N_2)$ (°C)
1	99.6	96.4	3.2	99.1	99.6	−0.5
2	101.6	97	4.6	100.1	100.8	−0.7
3	98.7	95.7	3	103.6	103.1	0.5
4	104.2	99.4	4.8	104.4	103.2	1.2
5	104.7	99.7	5	104.2	103.5	0.7
Av	101.8	97.6	4.1	102.3	102.0	0.24
Std dev	2.68	1.81	0.94	2.49	1.74	0.81

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Dr. Bassam Z. Shakhashiri in 2013. Examples of other Climate Science Challenge Grants are available on the ACS Climate Science Toolkit Web site.

The experiment was developed and student tested in the first semester of a two-semester general chemistry course sequence for STEM majors at UMaine during five semesters (Summer 2013, Fall 2013, Spring 2014, Summer 2014, and Fall 2014). Formative assessment data from students and lab instructors informed iterative modifications of the lab experiment. A preliminary report on the experiment and data presented in this work were presented at the ACS symposium "Citizens First: Communicating Climate Science to the Public" in March 2015.[28]

ASSESSMENT

Assessment was conducted during the Fall 2014 semester with an enrollment of 584 students: 419 students (72%) gave consent and participated in this University of Maine IRB-approved study. A total of 10 questions, all soliciting a text response, were asked (see Supporting Information Assessment Details (pdf and doc) for the complete list). Responses to four of the 10 questions are reported in detail in this work, while responses to all 10 questions were analyzed for the occurrence of common misconceptions. Two of the 10 questions were given to all students (n = 419); these two questions assessed student use of the PhET simulation and the ACS Science Climate toolkit, respectively, and are reported in detail in this work. For the remaining eight questions, students were divided into two groups, with each group answering four of the eight questions. This was done to minimize the total number of postlab questions that each student had to answer, since each question asks students to provide a text response. One question from each group was selected for analysis in this work.

Student responses to prelab questions were collected before students downloaded the experimental procedure, and postlab responses were collected approximately 1 week after the lab experiment was completed. Student responses were not used as part of their lab grades. Data were collected online using the InterChemNet course management system developed at the University of Maine.[29]

Student Evaluation of Online Resources

An integral part of the lab procedure was the use of two distinct online resources, the PhET simulation, "Molecules and Light", and the ACS Climate Science Toolkit. Each resource was meant to improve students' understanding of greenhouse gas mechanisms and the resulting implications for atmospheric warming. The interactive PhET simulation allows students to explore and experiment with a dynamic visualization of how light interacts with molecules in our atmosphere. The ACS Toolkit is a reliable source of textual and visual scientific information about greenhouse gases and atmospheric warming. To evaluate student use of online resources, all students were asked the following two postlab questions: "What information was provided to you by the ACS Science Climate Toolkit website?" and "Did the PhET simulation provide insight for you? Please explain." Categorized postlab responses to these questions were analyzed by a single researcher and are presented in Tables 2 and 3.

ACS Toolkit. To understand the use of the ACS Climate Science Toolkit, all students (n = 419) were asked: "What information was provided to you by the ACS Climate Science Toolkit?" Of the students who provided a written response (n = 394) most identified one or more scientific concepts. Responses were categorized according to the type of concept identified (shown in Table 2), and responses could be placed in more than one category. The most common type of response (43%) was that the toolkit provides a concrete definition of "greenhouse gas" and/or identifies specific properties of greenhouse gases related to their molecular structure and vibrations.

Table 2. Categorized Postlab Responses for the Question: "What Information Was Provided to You by the ACS Science Climate Toolkit Website?"[a]

Type of Information Identified as Useful	Students' Responses, % (n = 394)
(Molecular) properties or definition of "greenhouse gas"	43
Effect of greenhouse gases on the Earth, atmosphere, greenhouse effect, global warming	38
How greenhouse gases interact with IR radiation on a molecular scale	30
Misc. other	13
I do not know/not helpful	15

[a]The total is >100% because some responses fall into more than one category.

For example, one student wrote, "The ACS Science Climate Toolkit explained to me what a typical greenhouse gas looks like (a 3-atom molecule)." The second most common response (38%) was that the toolkit explains how greenhouse gases affect the Earth and atmospheric temperatures: for example, "This toolkit gave us the information about how greenhouse gases work and warm the atmosphere." Almost as prevalent (30%) were responses indicating that the toolkit supplies information about the interactions between IR radiation and greenhouse gas molecules ("Visual description of how IR light interacts with a variety of molecules."). Relatively few students (15%) gave responses that imply indifference about or lack of usefulness of the ACS Web site information.

PhET Simulation. When asked to explain how the PhET simulation provided insight toward the lab topic, of the 368 students who answered, most identified one or more scientific concepts and/or practices they developed by using the simulation. Responses were categorized according to the concepts identified, and they are shown in Table 3. The most common response (39%) was that the simulation provides insight on how radiation and gas molecules interact, as illustrated by this representative response: "the PhET

Table 3. Categorized Postlab Responses for the Question: "Did the PhET Simulation Provide Insight for You? Please Explain."[a]

Type of Information Identified	Students' Responses, % (n = 368)
How radiation and gas molecules interact	39
Visual representation of molecular-scale phenomenon	35
Which gases absorb or deflect IR	24
Identification/characterization of greenhouse gases	24
Misc. other	10
Not helpful	9

[a]The total is >100% because some responses fall into more than one category.

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Table 4. Rubric Scoring Description and Examples of Verbatim Student Responses in the Three Categories of Understanding of the Properties of Greenhouse Gases, Based on the Question "Please Explain How You Could Identify a Molecule That Is a Greenhouse Gas."

Student's level of understanding of properties of greenhouse gases	[Rubric Description] *Example student answer* Researcher notes
Incorrect	[Student demonstrates no understanding or very poor understanding of properties of greenhouse gases: • uses inaccurate terms to describe the function of greenhouse gas molecules, such as they reflect IR/heat/light, react with UV light, react with ozone • uses inaccurate terms to describe the structure of a greenhouse gas molecule • response is not clear or does not address the question]
Student 16576	*"It will have a carbon backbone."* Notes: Description of the molecular structure is incorrect
Partially Correct	[Student demonstrates some (incomplete) understanding of one or more properties of greenhouse gases: • partially describes a key structural property of a greenhouse gas molecule • partially describes a function of a greenhouse gas • gives one or more correct example(s) of a greenhouse gas • indicates that greenhouse gases contribute to atmospheric warming]
Student 16290	*"Polar molecules are generally greenhouse gases."* Notes: Incomplete description; not all greenhouse gases are polar
Correct	[Student demonstrates complete understanding of one or more properties of greenhouse gases: • accurately and completely describes one or more key structural properties of a greenhouse gas molecule • accurately and completely describes one or more functions of a greenhouse gas • describes the temperature effects of a greenhouse gas vs. a non-greenhouse gas based on lab experimental results (operational definition)]
Student 16263	*"A greenhouse gas must be composed of a molecule that is held together with weaker bonds that are more bendable and able to vibrate in the presence of infrared radiation."* Notes: Describes a structural property of a greenhouse gas

simulation provided an interactive [that] allows you to expose different kinds of molecules to different kinds of light and see what happens." With similar frequency (35%), students recognized the usefulness of visual representation offered by the simulation, indicated by such responses as "Yes it gave me a visual representation of what was happening on the molecular level" and "...shows the molecules jiggling." Twenty-four percent of students wrote that the simulation helped them understand which specific atmospheric gases absorb IR radiation. An equal percentage (24%) indicated that the simulation helped them identify structural characteristics and IR-induced molecular motions that define greenhouse gas molecules. For example, "...it showed me the movement of the molecules and I could make connections between the ones that did vibrate and the ones that did not." Only 9% of the students indicated dissatisfaction with the usefulness of the PhET simulation. For example, students suggested that it was not helpful because "it was too vague" or "...a simple model that didn't explain much."

Assessment of Student Understanding of Greenhouse Gases, the Greenhouse Effect, and Misconceptions

The lab experiment introduces students to climate science and focuses on the mechanism of how greenhouse gases absorb infrared radiation. To assess learning in this experiment, we selected two questions from the set of 10 for analysis: (1) "Please explain how you could identify a molecule that is a greenhouse gas." And (2) "Why don't atmospheric greenhouse gases "block" incoming solar radiation? Please explain." Question 1 was chosen to assess how well students were able to synthesize information from the various parts of the lab exercise (PhET simulation, ACS toolkit, and spectrometer lab) in order to describe structure and/or function of a greenhouse gas. Question 2 was selected to probe student thinking about the greenhouse effect that may reveal misconceptions.

Identification of Greenhouse Gases. Students (n = 198) were asked, "Please explain how you could identify a molecule that is a greenhouse gas." Both pre- and postlab responses were provided by 191 students. A rubric for scoring these responses was developed (see Supporting Information Assessment Details (pdf and doc) and validated by having two researches score 50 of the 198 responses with inter-rater reliability greater than 95%. After agreement was reached on the rubric, a single researcher scored the remaining student responses. The level of understanding of each response was evaluated as correct, partially correct, or incorrect (outlined in Table 4; see Supporting Information Assessment Details (pdf and doc for additional details). The data indicate a pre- to postlab improvement in understanding of concepts involved in identifying greenhouse gases (see Figure 3). The number of incorrect responses (which includes "I don't know") diminished by 67% (94 to 31), while the number of correct responses more than doubled (57 to 120).

Exploring Student Ideas about Atmospheric Greenhouse Gases and Solar Radiation. To assess a more complex topic related to the greenhouse effect, solar radiation and atmospheric greenhouse gases, students (n = 221) were asked, "Why don't atmospheric greenhouse gases "block" incoming solar radiation?" A single researcher analyzed the results of this question, finding that of the 203 students who responded to both pre- and postlab questions, many students correctly stated that radiation is absorbed rather than physically blocked. Approximately 19% (38/203) explained the distinc-

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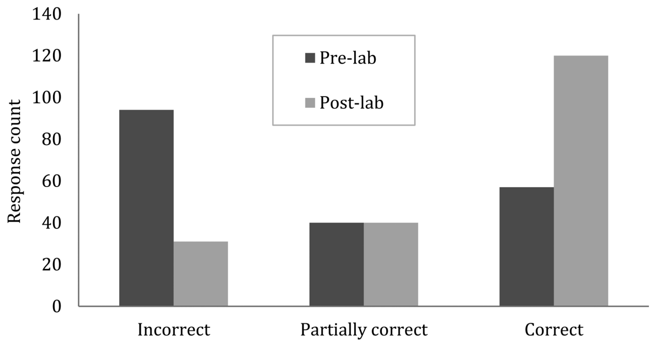

Figure 3. Quantitative assessment of pre- and postlab conceptual understanding based on 191 student responses to the question ″Please explain how you could identify a molecule that is a greenhouse gas.″.

tion between Earth's incoming (UV) and outgoing (IR) radiation, but there was only a slight increase in the number of students (42/203) who made this distinction after completing the lab procedure (see Figure 4). The majority of students did not distinguish between UV and IR radiation in their answers, or simply answered "I don't know." Implicit in the question is the idea that solar radiation is in the form of UV and visible light which are not absorbed by greenhouse gases. Many students were unaware of this, and thus did not distinguish UV from IR, which is part of a common misconception.[16,24] The lack of being able to distinguish UV from IR or a lack of change pre- to postlab is apparent in Figure 4.

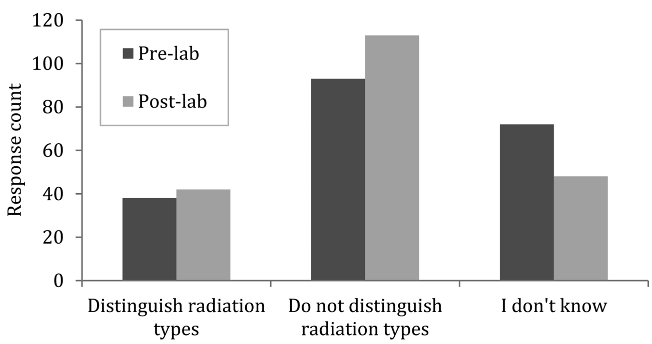

Figure 4. Characterization of the extent to which 203 students discern between UV and IR radiation in atmospheric processes based on the pre-/postlab question, "Why don't atmospheric greenhouse gases 'block' incoming solar radiation?"

The fact that students did not understand that incoming solar radiation is composed of UV radiation nor distinguish one type of radiation from another (UV vs IR) is not surprising especially since the laboratory activity focuses entirely on infrared radiation. Thus, the type of radiation that occurs in solar radiation was not considered.

It is interesting to compare expectations of the two questions discussed above. While the first question was expected to be influenced by the activities student performed during the experiment (and was found to be), the second question was not expected to be influenced, since the lab experiment neither was directly about solar radiation or about the influence of solar radiation on atmospheric greenhouse gases. These data suggest that building a sound understanding of greenhouse gases and absorption phenomena, developing a more sophisticated view of the complexity of the greenhouse effect, and reducing misconceptions may take a series of well-integrated laboratory activities rather than a single one.

Sampling Student Misconceptions. Finally, a single researcher examined student responses to all pre-/postlab questions (see Supporting Information Assessment Details (pdf and doc) for the occurrences of common student misconceptions. A few examples are provided here. An evaluation of all prelaboratory responses revealed that 58 out of 419 students (14%) held the misconception that greenhouse gases interact with stratospheric ozone. Most indicated that greenhouse gases play a role in depleting or otherwise negatively impacting the ozone layer. Example prelab statements describing this interaction include "Greenhouse gases, such as CO_2, cause holes in the ozone layer, which is responsible for shielding us from harmful UV and Infrared rays" and "greenhouse gases participate in increasing the temperature of the earth by keeping the heat inside the ozone layer and not letting it go out." After completing the laboratory, only 10 students (2%) implied this erroneous relationship.

The prelab responses also show that 63 students (15%) used various descriptions implying that greenhouse gases are a physical barrier to energy exchange in the atmosphere. The incidence of this misconception decreased in postlab responses to 45 students (11%). In our analysis, we included responses containing words such as "layer," "barrier," "reflect," "bounce," "blanket," and/or similar terms that convey the meaning of the gases acting as a physically resistive blockade to radiation. Examples of this type of response include, "Greenhouse gases are the cause of global warming and what those gases do is create a layer that doesn't allow those rays to go back into the atmosphere which results in the earth heating up", "the layer of our atmosphere acts as a mirror allowing little of the radiation to pass through and reflecting the rest into space", and "...the gases make a blanket that traps the radiation...."

While our analysis is far from comprehensive, our sample indicates a significant number of students have misconceptions. This is consistent with findings from other recent studies which illustrate that students hold many misconceptions about the greenhouse effect and climate change.[13,24] Although there is evidence that the lab experiment reported here helps students understand the mechanism of infrared absorption by greenhouse gases, which is a fundamental concept for developing an understanding of the greenhouse effect,[30] developing additional activities to build upon this understanding appears necessary.

CONCLUSIONS

This lab experiment provides an introduction to climate science through laboratory inquiry into the thermal effects of molecular absorption of infrared radiation by greenhouse and non-greenhouse gases. A novel feature of the experiment involves a simple, student built, low-cost infrared spectrometer, using a hot plate (IR source), a plastic cuvette holder (to standardize path length), and an infrared thermometer. Students explore a PhET simulation, design experiments to compare the absorption of IR light on different samples of gas, visit the ACS Climate Science Toolkit, and construct and present a poster in lab.

Assessment data for a pre-/postlab question about identifying greenhouse gases revealed that the number of incorrect responses diminished by 67% while the number of correct responses more than doubled. Analysis of student responses before the experiment (i.e., prior knowledge) indicated that 14% of students held the misconception that greenhouse gases

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interact with stratospheric ozone and that greenhouse gases play a role in depleting or otherwise negatively impacting the ozone layer. Analysis of poststudent responses indicated that occurrences of this misconception decreased to only 2% of student responses.

Student responses to postlab questions indicate that the PhET simulation (1) provided useful information about how radiation and gas molecules interact, (2) helped to visualize dynamic phenomena at the atomic scale, (3) helped identify which gases absorb or deflect IR, and (4) helped to identify or characterize greenhouse gases. The student responses to postlab questions about use of the ACS Climate Science Toolkit indicated that this online resource provided information about the molecular properties and/or the definition of "greenhouse gas", the effect of greenhouse gases on the Earth, atmosphere, greenhouse effect, and global warming, and how greenhouse gases interact with IR radiation on a molecular scale.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00047.

Further details of the assessments (PDF, DOCX)
Student laboratory procedures (PDF, ZIP)
Instructor notes (PDF, DOCX)

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Notes

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