ABSTRACT
We have developed and tested a multifaceted curriculum for use in introductory earth science classes from the secondary-school to the introductory undergraduate level. The centerpiece of this curriculum is a project-based investigation of greenhouse warming that can be conducted during one or more lab sessions using off-the-shelf materials. Other facets of the curriculum include: 1) literature review, 2) review of popular-press coverage, 3) assessment of internet-based information, and 4) interviews of fellow students. Simulation of the greenhouse effect utilizes two fish tanks, heat lamps, and either laboratory thermometers or laptop-driven temperature probes. Experiments are run by creating a CO2-enriched environment and measuring the differential heating of that experimental apparatus compared to an identical control. This experiment can be run as a hands-on student project or by the instructor as a demonstration for larger lecture classes. This greenhouse experiment and the broader curriculum have been developed around the central theme of teaching students to distinguish (1) solid scientific mechanisms from (2) actively debated hypothesis from (3) the broader genre of misperception and misinformation. This process provides students the opportunity to gain a much deeper understanding of the climate system, the nature of scientific uncertainty, the burden of proof in ongoing research, and the difficulties in transferring scientific results to the public-policy realm.

Keywords: Earth science; meteorology; climate change; greenhouse effect; global warming; education - undergraduate; education - secondary; teaching and curriculum.

INTRODUCTION
Global climate change is one of the most contentious scientific and political issues of our time. Partly because of this debate, this issue provides an opportunity for students to gain a much deeper understanding of the climate system, the nature of scientific proof, and the friction at the boundary between science and public policy. Despite the widespread discussion of climate-change issues in the public realm, or very possibly because of it, misconceptions and outright untruths abound. The primary goal of the curriculum presented here is to help students separate the solid scientific foundation beneath many of these issues, from legitimate debate at the cutting edge of current research, from clear misstatements motivated either by politics or simple misunderstanding.

We have found that a good starting place is to formally define several terms:

Greenhouse effect: asymmetry of the atmosphere, in which carbon dioxide, water vapor, and other gases are more transparent to incoming solar radiation than they are to outgoing radiation of heat, thereby keeping the Earth warmer than it would otherwise be.

Global warming: increase in average temperature around the Earth. It has been suggested that recent increases have been caused by increasing concentrations of greenhouse gases in the atmosphere.

Climate change: changes in the broader range of conditions - including temperature, precipitation, circulation, and the occurrence of extreme weather - that occur over large regions and are sustained over long periods of time.

These distinctions are important in helping students understand that the greenhouse effect is not itself an anthropogenic phenomenon, that it occurred on Earth long before humans appeared on the scene, and that it is a process that operates on other planets as well. A surprising number of students come to the classroom believing that “the greenhouse effect” refers specifically to anthropogenic heating. Especially when predisposed to doubt human-induced global warming, students often “throw the baby out with the bath water,” believing that the greenhouse effect is an unproven scientific theory, environmental propaganda, or even some sort of scientific conspiracy.

Although most students are surprised to hear it, the greenhouse effect is a physical process well known by atmospheric chemists and physicists for nearly two centuries. In the early 19th century, Joseph Fourier concisely described the process by which “light finds less resistance in penetrating the air, than in repassing into the air when converted into non-luminous heat” (Christianson, 1999). In 1896, the Swedish scientist Svante Arrhenius calculated that doubling the CO2 concentrations in the Earth’s atmosphere would raise average global temperature by 5-6°C (Uppenbrink, 1996), an estimate that is not entirely outside
the range suggested by state-of-the-art models today (2.0±0.6°C; Kattenberg et al., 1996). More surprisingly still, the greenhouse effect operates even on very small scales so that it can be demonstrated using common laboratory supplies.

The basic idea of “greenhouse in a bottle” experiments has been elaborated by several previous authors. Gutnik (1991) outlines a number of different experiments that illustrate principles of the climate system, including the greenhouse effect. Various activities in the Gutnik volume are designed to illustrate anthropogenic emissions, the role of the atmosphere in the Earth’s thermal balance, and some of the potential effects of global warming. Bohren (1991) presents a classroom activity that demonstrates the links between temperature and radiation of heat. Golden and Sneider (1989) present an exercise entitled “Exhaust and Exhalation”, in which students can compare the relative concentrations of CO$_2$ in gas samples from different sources. Finally, Hocking et al. (1997) developed a curriculum for students grades 7-10 that illustrates aspects of the greenhouse effect involving experiments, activities, and a summative role-playing exercise. We see the experimental portion of the curriculum outlined here as the capstone of the project and anticipate that many educators may prefer to use the experiment alone as a lab or lecture demonstration.

**PROJECT-BASED CURRICULUM**

We present here a five-part, project-based curriculum as it was developed for high school classes at Marion, IL High School. The same project has been run with groups of introductory environmental geology students at Southern Illinois University, and it also works well at that level. In both cases, students were subdivided into groups of 3-4, with each group assigned one of the following tasks:

1) Highlights of the scientific literature
2) Review of the popular press
3) Climate-change resources on the internet
4) Peer interviews
5) Lab experiment

Following completion of these tasks, students assembled their findings for written reports and for oral presentations to the entire class. The elements of this curriculum seem to help students appreciate the multifaceted nature and varied perspectives on climate-change issues.

**Scientific Literature** - Although a complete review of the pertinent literature is far beyond this paper and beyond the students for whom this curriculum is designed, careful selection of broad-based review articles seems to put the issues within students’ grasp. A few critical papers were selected for this group of students to read, discuss, and digest. We culled the literature for articles that were short and at a reasonable technical level; this often meant using review or introductory articles in *Science* and *Nature*. Some of the issues that we felt were most critical and current, and the associated papers and listed here:

- **Global cooling**: Kukla and Matthews (1972), Colligan (1973)
- **Surface temperature vs. satellite measurements**: Kerr (1998), McDonald (1999a), Vogel (1995)
- **Carbon-dioxide sinks**: Kaiser (1998)
- **Role of atmospheric aerosols**: Schwartz and Andreae (1996), Kiehl (1999), Rasool and Schneider (1971)
- **Water vapor in the atmosphere**: Rind (1998)
- **Natural climatic variability**: Overpeck (1995), Lamb (1995)

Past scientific predictions of global cooling are often raised to discredit current predictions of global warming. It’s important to place these earlier predictions in the correct context. Oxygen-isotope records from deep-sea cores provided the first high-resolution records of glacial-interglacial climatic fluctuations, really giving birth to modern paleoclimatology. Revelation of these past fluctuations naturally led to speculation about when the present interglacial will end.

Perhaps the most debated question in global-warming research today is the purported discrepancy between surface measurements of average temperature trends and microwave measurements from satellites. The surface record comes from the thousands of weather stations scattered across the globe, with systematic measurements that stretch back to the middle of the 19th century. These weather stations suggest a warming trend of 0.3°C-0.6°C in the past 150 years (Ledley et al., 1999), with proxy data showing warming of about 1.0°C in the past 500 years (e.g., Pollack et al., 1998). In contrast to the surface measurements, analysis of satellite data dating back to 1979 show a modest cooling trend during that time (Christy and Spencer, 1995). Critics of the surface-based measurements suggest (1) that they disproportionately weight the continental areas of North America (where the weather stations are concentrated), and (2) that they show systematic errors introduced by local changes such as urbanization around the measurement stations. Critics of the satellite data suggest that, although they are precise, they are inaccurate because of orbital and other errors, and indeed, subsequent corrections now suggest either more modest cooling or a very slight warming trend (Schwartz and Andreae, 1996).

An important point for students to grasp is that the numerical models (the General Circulation Models, or GCMs) now being used to predict the sensitivity of the Earth’s climatic system have been refined through several iterations in recent years. Mismatch in early model results led to the recognition that major sinks such as oceans and soils seem to store about one-half or more of the CO$_2$ added to the atmosphere (Kaiser, 1998; Lamb, 1995). A few years later, lingering model errors made clear the importance of atmospheric aerosols in the overall climate system (Kerr, 1995; Schwartz and Andreae, 1996; Kiehl, 1999). Many researchers also now point to the role of water vapor as another, potentially important, uncertainty. Rather than viewing such periodic revision of the models as cause for their repudiation, students should understand that this is part of the scientific process (Hansen et al., 1998).
Finally, several simple but scientifically rigorous reviews discuss natural climatic variability and its implications for anthropogenic climate change. Some of the mechanisms that may dramatically shift the Earth’s climate in the absence of human action include orbital cyclicity (the “Milankovitch” mechanisms), variability of solar input (the sunspot cycle), volcanic activity, and others (Lamb, 1995). The magnitudes of climatic shifts in the geological record provide perspective on recent trends, illustrating (1) that natural swings greater than the inferred greenhouse warming have indeed occurred numerous times, but also (2) that changes of just a few °C do not sound like much, but they represent enormous shifts in the environment. A good concluding perspective is the carefully worded statement in the American Geophysical Union position paper, “There is no known geological precedent for the transfer of carbon dioxide, in quantities comparable to the burning of fossil fuels, without simultaneous changes in other parts of the carbon cycle and climate system” (AGU, 1999).

**The Popular Press** - One of our student groups was assigned the task of assembling and analyzing articles on climate change from the popular press. By scanning current and past issues of newspapers and magazines, students gain insight on the particular slants and filters that the media apply to the science. For example, our students found a striking correlation between the weather-of-the-moment and concurrent press coverage of climate-change issues—from out-dated global-cooling theories paraded out during winter cold snaps (e.g., Lemonick, 1994) to blizzards of global-warming articles during hot spells (e.g., Kaplan, 1996). A direct account of the contrasting goals and approaches of scientists and members of the media can be found in McDonald (1999b), which describes the “public-relations fiasco” that resulted from the cautious wording of the AGU position paper on global warming (AGU, 1999).

**Internet Resources** - Another of our student groups gathered information available on the Web. Not surprisingly, the range of opinions expressed in this medium covered a much broader spectrum, and the occurrence of marginal information and misinformation was much greater. A list of a few interesting hosts include:

- National Oceanic and Atmospheric Administration
- National Aeronautics and Space Administration
- British Broadcasting Corporation
- Environmental Defense Fund
- Cato Institute
- Heartland Institute

**In-School Interviews** - The fourth source of global-warming information assessed by our students was the spectrum of opinions in their own schools. Our students interviewed their peers, teachers, and school administrators, quizzing them about technical details of the greenhouse effect and asking their opinions about warming and climate change. Some interviewees (students, in fact) expressed remarkably clear and deep understanding of the physical mechanisms, whereas other responses were... less sound:

- “It’s not true. It is all political lobbying.”
- “It [the greenhouse effect] causes the ozone layer to deplete.”
- “It causes skin cancer and sun poisoning.”
- “I think it [the greenhouse effect] causes hair loss.”
- “Don’t your teeth fall out?”
- “There won’t be any consequences in my lifetime.”

All interviews were videotaped, and the students edited a ten-minute compilation that was presented to the group as a whole in the summative overview. The same interviewing and videotaping was done by SIU students, with some improvement in the ratio of knowledgeable to off-base responses, but with a comparable range of misinformation in the latter category.

**GREENHOUSE DEMONSTRATION**

The centerpiece of this curriculum is an experimental procedure that can be used as a student laboratory exercise, as a lecture demonstration, or as part of the broader project described above to investigate global climate and climate change.

**Laboratory Set-Up** - Materials necessary for this activity include the following:

- 2 identical fish tanks (2.5 or 5 gal)
- 2 or 4 heat lamps, 150 or 250W
- 4 or 6 ring stands (# of lamps + 2)
- 2 burette clamps
- Dark sand or other substrate
- 2 shallow glass or plastic dishes
- 2 thermometers (0.1° C precision)
- 2 glass covers (optional)
- Stop watch (or clock with sweep hand)
- Matches
- Wax crayon
- Filter paper
- Vinegar
- Baking soda
- Spoon
- Long stirring rod
- Forceps (or thread)
- Goggles

The two tanks should be placed side-by-side with 5-10 cm between them as illustrated in Figure 1. Using the wax crayon, one tank should be marked “A” (experimental) and the other “B” (control). Evenly distribute the dark substrate (black sand or aquarium rocks) over the bottom of both tanks. Using two of the ring stands and the burette clamps, mount one thermometer inside each tank, with its base 2-3 cm above the substrate. The thermometers should be located and oriented so that they can be easily read when the experiment is underway without moving them and without reaching above the tanks. Place one dish, face-up, in the center of each tank. The dishes should be...
Experimental Procedure - The experiment should begin with tanks at room temperature and with the heat lamps off. As discussed in the following section, the reaction alters the temperature in the tanks, and can give misleading results if the tanks are preheated. If more than one run is planned for the same class period, allow several minutes for cooling between experiments.

When ready, turn on the heat lamps and add the correct quantity of vinegar to the baking soda in the tank A. Add the vinegar slowly so that the dish does not overflow. Stir the reactants to make sure that all of the baking soda is used up. If your students are sticklers for detail, an equal quantity of vinegar (or water) can be poured into the dish in tank B. Now light a match and lower it into tank A using the forceps. The level at which the match is extinguished is the top of the carbon dioxide layer. Because the carbon dioxide is denser than air, this layer should persist within the tank for at least 5-10 minutes even with no lids in place. Of course, excessive turbulence in the vicinity of the tanks should be avoided. To minimize CO2 loss, you can cover the tanks with glass lids, but as discussed later, this is not required for good results. When the match test is completed, begin timing the experiment. The time elapsed between the first addition of vinegar and the start of the clock should be no more than one minute.

At the start of the experiment note the temperatures in the two tanks. Repeat these measurements at regular intervals, we recommend at least every 30 seconds, until the temperatures in both tanks begin to plateau. Depending on the size of the tanks, the quantities of reactants used, and the number and wattage of bulbs, each experimental run may last from 5 to 20 minutes. If class time permits more than one run, some options include switching the positions of tanks A and B (to show that the bulbs are not the cause), varying the quantity of the reagents, or using some of the variations outlined in the following section. As noted above, if multiple runs are planned, turn off the lamps and allow time for cooling between experiments.

Results, Warnings, and Variations - If all goes well, the results of this experiment should resemble the results illustrated in Figure 2. The experimental tank should heat faster and to a higher peak temperature than the control tank. With all other factors equal, the differential heating can be attributed to the effect of the carbon dioxide in the experimental tank. In the spirit of “seeing is believing”, this demonstration shows students that the greenhouse effect is the global manifestation of a simple and well known physical phenomenon.

As noted above, it is important to begin this experiment with the tanks near room temperature and to allow a minute or so between turning the heat lamps on and the first temperature measurement. One complicating factor in this procedure is that this particular CO2-producing reaction is endothermic (Figure 3). During the reaction itself, the temperature in the experimental tank may dip substantially. If a sufficient quantity of reagents are used, then the temperature in tank A rapidly makes up the difference and becomes warmer than tank B. Other instructors may have a different philosophy, but we chose to steer our students clear of this complication. The vinegar-baking soda reaction itself is not analogous to the processes that put CO2 into the Earth’s atmosphere (fossil fuel combustion is of course exothermic), and the short-term cooling is not relevant to the analogy demonstrated here.

One cautionary note to relay is the result of frustrating personal experience. There is a strong temptation to use aquarium lids to reduce the loss of CO2 from the experimental tank over the duration of the run. We had transparent fiberglass lids fabricated for both tanks, but for reasons that remain not altogether clear to us, these lids

Figure 1. Schematic illustration of the experimental apparatus.
seem to completely suppress the differential heating of the two tanks. As several textbooks note, the “greenhouse effect” is a misnomer because greenhouses stay warm through an entirely different mechanism – the glass prevents conductive and convective heat loss – so that the insulating effects of the fiberglass lids may have overwhelmed the greenhouse warming in the tanks. It is worth noting, however, that we later did get good results using glass lids. Partially because of the early frustration and partially because of our own uncertainty about the mechanisms at work, we have used open tanks ever since. As noted earlier, the carbon dioxide is denser than air, so that it persists in the tank for some time.

One major variation in the above procedure that worked extremely well for us was to replace the thermometers in the experimental apparatus with computer-driven temperature probes. We used a pair of probes connected to a laptop computer and controlled by a data-logging software package. The intervals between temperature measurements can be preset to as little as once per second, and measurements in the two tanks are precisely simultaneous. This hardware and this software are simple enough to operate that our students had no trouble. We anticipate, however, that the greatest utility of using the automated temperature probes would be when conducting this experiment as a demonstration for large lecture classes - after the initial set-up, the lecture could
proceed uninterrupted while the experiment takes its course, with real-time results appearing via an LCD display.

Other possible variations of this procedure have been suggested in the literature or have occurred to us while fine-tuning this methodology. For example, Gutnik (1991) suggested that the same basic procedure can be followed with the experimental tank containing a CO₂-depleted atmosphere by filling the dish in tank A with soda lime, which reacts with carbon dioxide and depletes it from the tank. Gutnik notes that glass tank covers are required and that the experiment should be run over the course of several hours. In a similar vein, we contemplated attempting the experiment with other greenhouse gases such as CFCs or methane, or perhaps with purported climate-coolers such as aerosols. One obvious alternative greenhouse gas to experiment with is water vapor, which may be the most important greenhouse gas in the Earth’s atmosphere. Steam would be easy enough to generate, but the water vapor probably would need to be introduced to the control tank at close to room temperature for the experiment to have much meaning.

CONCLUSIONS

The main thrust of both the laboratory demonstration presented here and the broader climate-change curriculum is to help students distinguish the solid science in these issues from the dizzying array of half-truths and untruths that they encounter in the press, on the internet, and even in casual conversation.

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