CLIMATE CHANGE TOOLKIT
The Greenhouse Effect in a Beaker

Standards
NGSS ESS3.D Global climate change
NGSS PS4.B Electromagnetic radiation
Grade Level: Middle School

Equipment
Heat lamp
1-liter beakers or jars (2)
Digital thermometers (2)
Small-diameter flexible tubing (~2 ft)
Flask with stopper (or similar)
$NaHCO_3$ antacid tables (4 per experiment)

Overview
The Sun emits radiant energy. Radiant energy is characterized by its wavelength. The electromagnetic spectrum maps out a range of energies from very short wavelength, high energy gamma rays (< 10^{-12} meters) to very long wavelength, low energy radio waves (1millimeter to 100 kilometers). Near the middle of this spectrum is the visible light that we are most familiar with (390 to 750 nanometers). The Sun emits most of its energy at visible wavelengths.

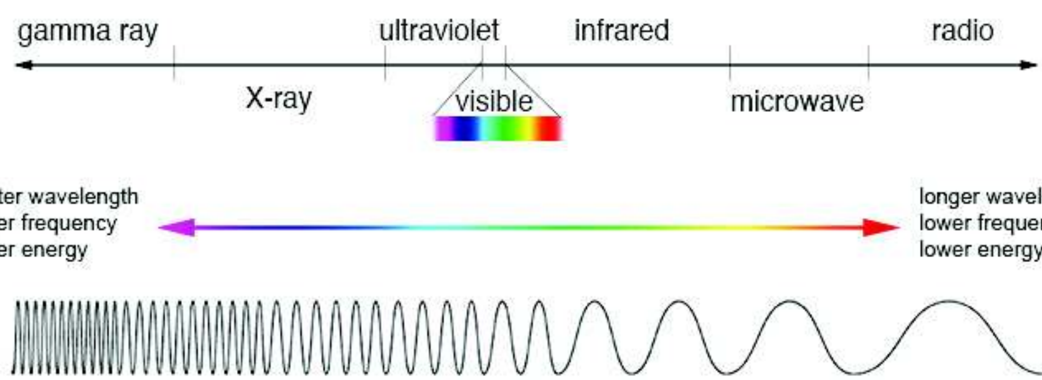


Figure 1: A simplified electromagnetic spectrum.

When sunlight shines on the Earth‘s surface the solar energy is absorbed. The surface is warmed by this absorbed energy, and it re-emits energy of its own. However, the Earth does not emit visible light like the Sun, rather, it emits infrared energy (IR). Energy at different wavelengths (short-wavelength visible, or long-wavelength infrared) interacts differently with different objects in the environment. For example, glass windows transmit visible light – it passes right through. But a glass window absorbs infrared light, preventing it from passing through. This is how a glass greenhouse keeps plants warm in cold weather. Sunlight passes through the glass windows, warms the interior, the interior then re-emits infrared energy, which is absorbed by the glass, keeping the warm air inside.

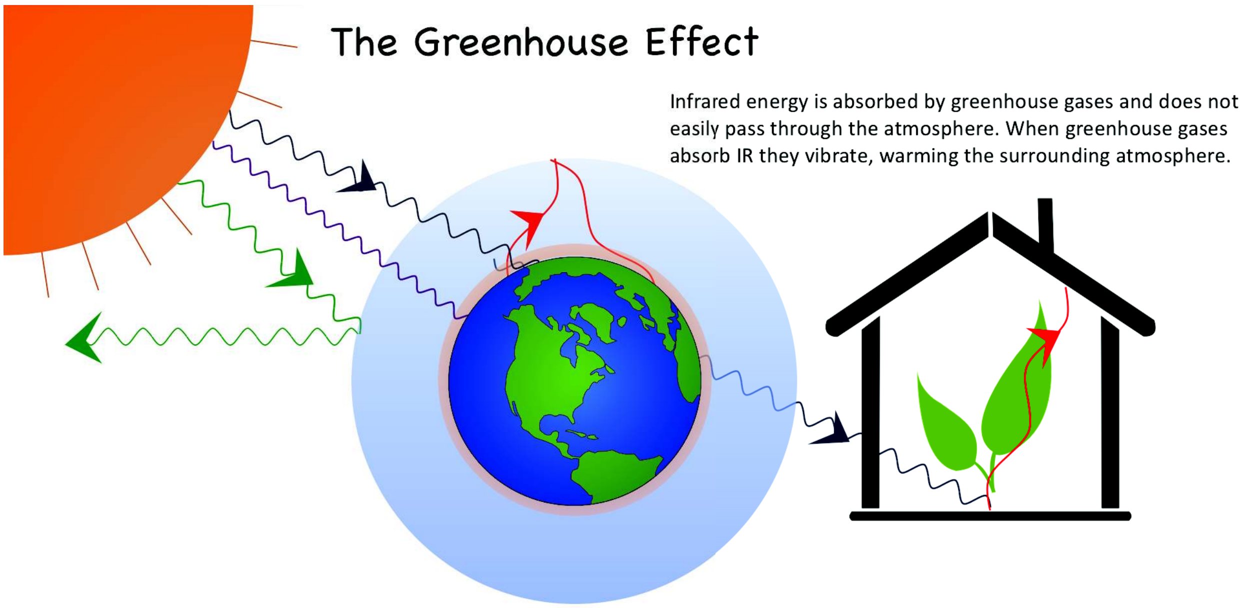


Figure 2: Diagram of the greenhouse effect. The Sun emits short-wavelength energy that passes through the atmosphere. It warms the Earth surface and is re-emitted as long-wavelength infrared energy. The infrared is absorbed by trace gases in Earth's atmosphere, keeing it warm.

Why?

The three most abundant gases in Earth's atmosphere are nitrogen (N_2), oxygen (O_2) and argon (Ar). These three gases are transparent to both visible and infrared energy, so sunlight passes through the atmosphere and warms the surface of the Earth. Other gases are transparent to visible light but absorb infrared – like the glass in a greenhouse – so we call these ***greenhouse gases***. Carbon dioxide (CO_2) and methane (CH_4) are greenhouse gases.

When a gas molecule absorbs IR energy it vibrates. Vibrations and collisions with other gas molecules raise the temperature of the atmosphere. A higher concentration of greenhouse gases leads to a warmer atmosphere. The atmosphere has always had greenhouses gases, and a small amount keeps Earth comfortably warm. However, too many greenhouses gases have the ability

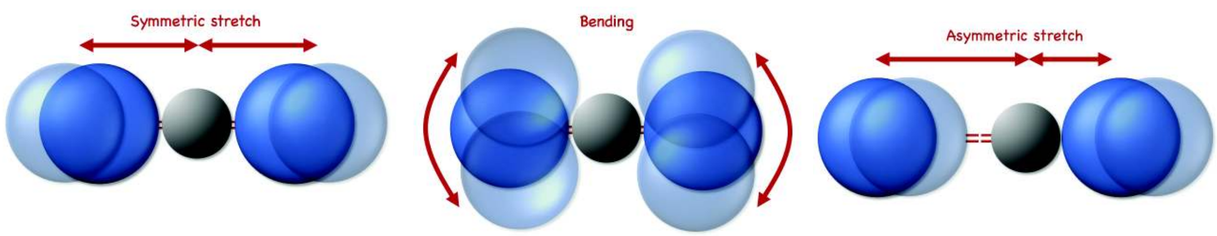


Figure 3: Carbon dioxide molecules vibrate when they absorb IR energy, either by bending the bonds in the molecule, or by stretching asymmetrically.

to raise the temperature of the atmosphere to a level that is harmful to natural ecosystems and human communities.

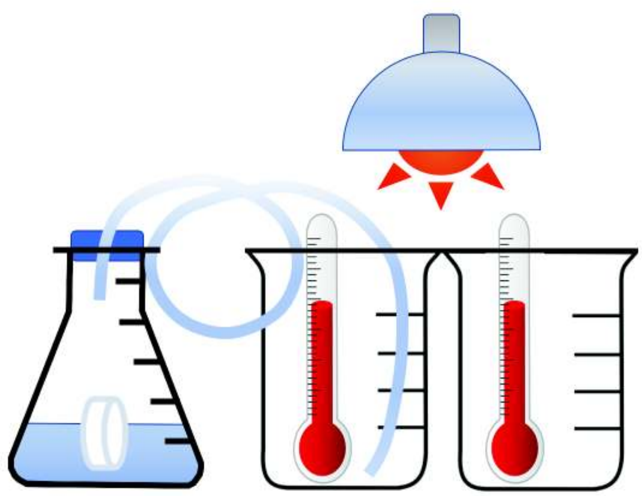
What?

Because both atmospheric gases and infrared energy are invisible, they can be difficult to study and to understand. But we can design experiments to make the invisible visible – or at least visible to some simple instruments and tools – that can help us visualize these processes. We can study the absorption of IR by carbon dioxide with a jar, a lamp, and a thermometer.

How?

Set up the experiment: When we design an experiment to look at changes in the environment the best approach is to create two identical systems; one that we will change, and one that we will leave unchanged, for comparison. The system that we change is the experiment, the system that we leave unchanged is the ***control***. In this experiment we will observe the atmosphere in two identical one-liter beakers (glass jars work too). A lamp with a high-intensity light bulb will supply the IR energy to the system (a chick incubator lamp, or reptile basking lamp from a pet store is a great source of IR energy). The carbon dioxide will be generated when we dissolve effervescent antacid tablets in water. We need thermometers to measure the temperature change, and a method for recording and graphing our data.

Figure 4: Experimental set-up



- Set up the lamp so that it can shine from above into the beakers.
- Position the two beakers under the lamp with the lamp illuminating both equally.
- Place one thermometer in each beaker.
- Fill the flask with ~250ml water, and arrange the tubing and flask stopper so that it is ready to seal the flask. Place the other end of the tubing into the experimental beaker.
- Let the system equilibrate with the lamp on – about 10 minutes – so that the two beakers are uniformly warm and at a stable temperature. This is important, since we will measure temperture change during the experiment, we need to ensure that the temperature is not changing before we start the experiment.

Notes: In this experiment we use an erlenmeyer flask with a stopper and plastic tubing to introduce CO_2 into the experimental beaker. This method ensures that the only change made in the experimental beaker is the addition of CO_2 gas, thus any recorded temperature change can be attributed to the CO_2. If an erlenmeyer flask is not available other containers can also be used – even a fast-food soda cup with a lid that fits a straw would work – as long as the tubing fits through the straw opening. The thermometers shown in the photo here are lab probes that interface with a computer (and/or smartphone) display. This is convenient but not essential. A digital thermometer will work better than a liquid-filled analog thermometer as it is far easier to read and record during the experiment. The beakers do not need to be sealed; CO_2 is denser than air and plenty of CO_2 will remain in the experimental beaker even with an open top. $NaHCO_3$ tablets dissolve in water to exsolve CO_2 gas; 4 tablets will ensure that the experimental beaker is flooded with CO_2. For the data shown on the following page, we used a dual temperature-CO_2 probe, which allows us to verify that CO_2 is entering the beaker - and - we can also observe the relationship between the timing of the CO_2 arrival and temperature rise. Again, this is helpful, but not essential.

Sample Data Sheet (partial)

Time	**Temp.experiment**	**Temp.control**
0:00		
0:15		
0:30		
0:45		
1:00min		
1:15		

Run the experiment: Use a smartphone or other timer to monitor the experiment for ten minutes. Record data at ~15-second intervals.

- Begin monitoring and recording the temperature in the two beakers for about 1 minute *before* adding the $NaHCO_3$ tablets – this establishes an additional baseline before beginning the experiment.
- At the one-minute mark add 4 $NaHCO_3$ tablets to the erlenmeyer flask, all at once, and immediately stopper the top of the flask.
- Continue recording the temperature in the experiment and control beakers for 10 minutes.
- Graph the data (Time in minutes on the x-axis, Temperature on the y-axis); plot both data sets (experiment and control) on the same graph.

Discussion

The experiment described here should produce a 1-2^{o}C temperature change over ten minutes of data collection. IR energy from the lamp excites the CO_2 molecules, causing them to vibrate. When they collide with other gas molecules in the beaker some of this vibrational energy is transferred to the other molecules, increasing their translational energy, or average velocity. The temperature of a gas is a measure of the average translational kinetic energy of the molecules, where kinetic energy is determined by the molecules' mass and velocity ($e = 1/2mv^2$). Because there is no change in the control beaker, the change we observe in the experimental beaker can only be attributed to the addition of CO_2 gas. In Earth's atmosphere the concentration of CO_2 is less than in our beaker (while our IR source is far less powerful), yet the same process occurs on a large scale in the atmosphere and is currently responsible for a rise in global atmospheric temperature.

Carbon Dioxide and Temperature: Experiment & Control

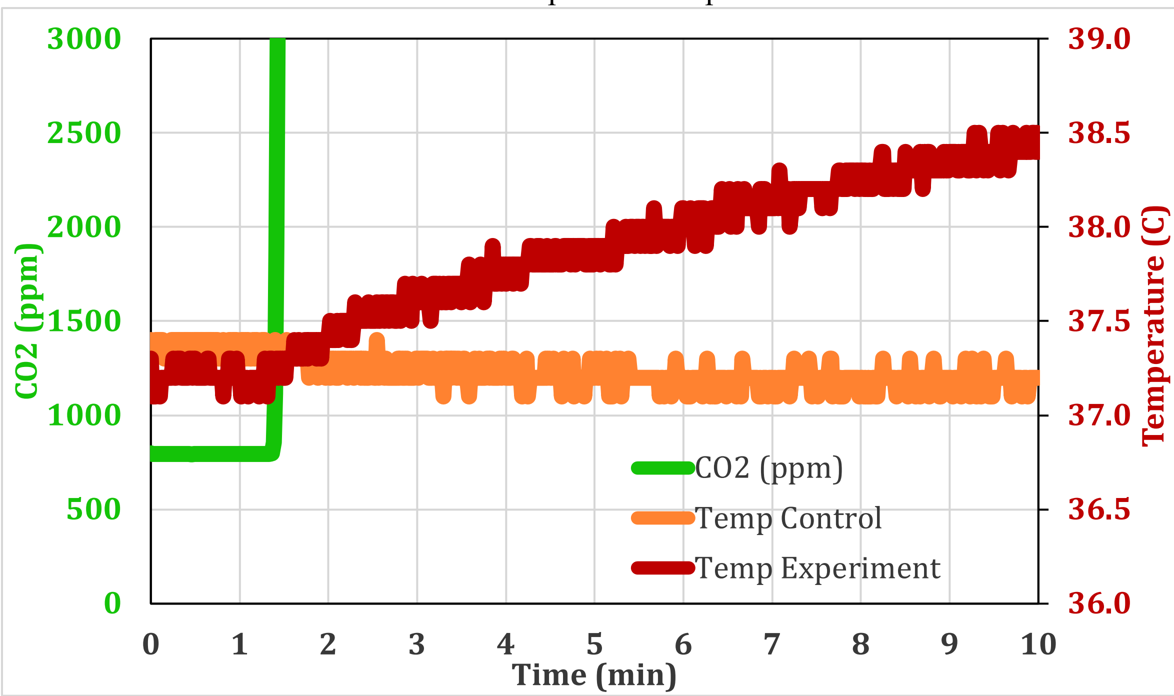


Figure 5: Sample data for experiment. CO_2 is introduced to the beaker at 1:30min; note that the temperature in the experimental beaker rises immediately, while the temperature in the control beaker does not change. The total temperature rise after 10 minutes is 1.3°C.

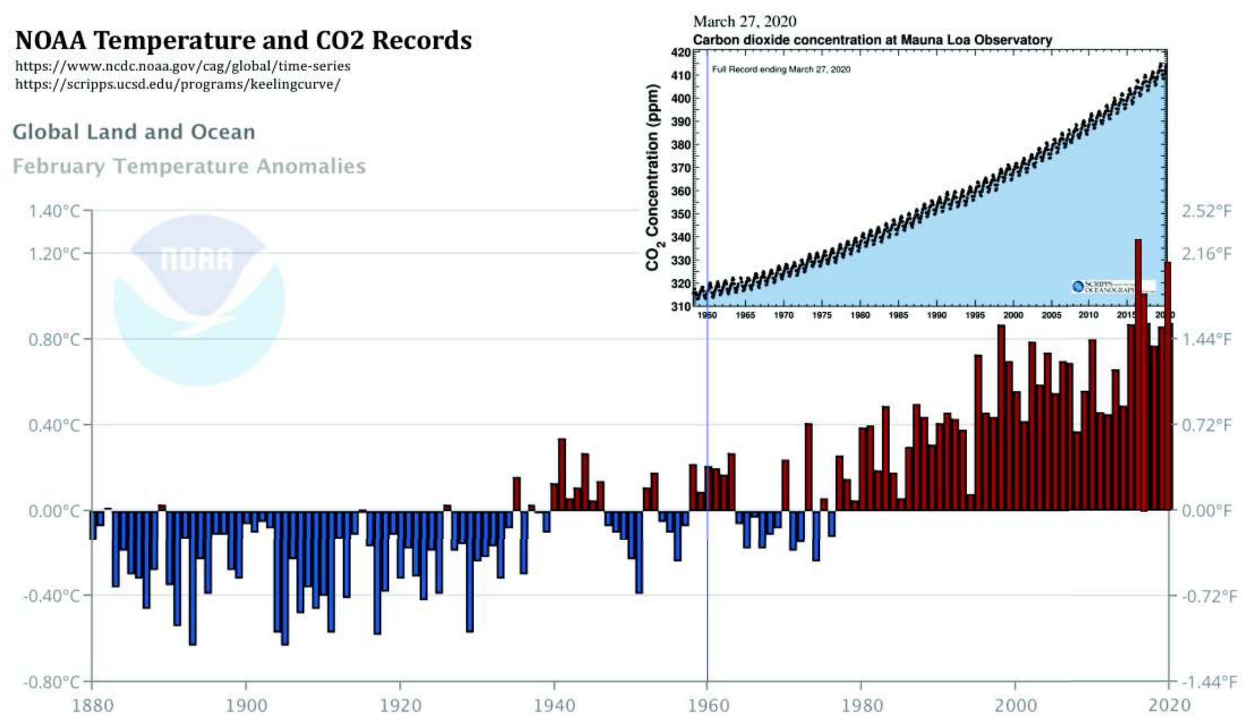


Figure 6: Measurements of atmospheric CO_2 concentrations (inset) and Earth surface temperature change.

Data Table

Time (min)	CO2 (ppm)	Temp.control (C)	Temp.Experiment (C)
0.00	797.00	37.4	37.3
0.25	794.33	37.4	37.3
0.50	793.67	37.4	37.3
0.75	795.00	37.4	37.2
1.00	794.67	37.3	37.2
1.25	795.67	37.4	37.2
1.50	30172.00	37.2	37.3
1.75	100020.00	37.3	37.4
2.00	100020.00	37.3	37.4
2.25	100020.00	37.3	37.4
2.50	100020.00	37.3	37.5
2.75	100020.00	37.2	37.5
3.00	100020.00	37.3	37.6
3.25	100020.00	37.2	37.7
3.50	100020.00	37.2	37.6
3.75	100020.00	37.2	37.6
4.00	100020.00	37.2	37.7
4.25	100020.00	37.1	37.8
4.50	100020.00	37.2	37.8
4.75	100020.00	37.3	37.9
5.00	100020.00	37.2	37.9
5.25	100020.00	37.2	37.9
5.50	100020.00	37.2	38
5.75	100020.00	37.2	38
6.00	100020.00	37.2	38.1
6.25	100020.00	37.2	37.9
6.50	100020.00	37.2	38.1
6.75	100020.00	37.2	38.1
7.00	100020.00	37.2	38.1
7.25	100020.00	37.3	38.1
7.50	100020.00	37.2	38.2
7.75	100020.00	37.1	38.3
8.00	100020.00	37.2	38.3
8.25	100020.00	37.3	38.4
8.50	100020.00	37.2	38.4
8.75	100020.00	37.2	38.4
9.00	100020.00	37.2	38.4

9.25	100020.00	37.3	38.4
9.50	100020.00	37.2	38.4
9.75	100020.00	37.2	38.4
10.00	100020.00	37.2	38.4

Resources

NOAA National Centers for Environmental Information - https://www.ncdc.noaa.gov/cag/global/time-series

Scripps Institution of Oceanography CO2 record - https://scripps.ucsd.edu/programs/keelingcurve/

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Graph for student data: