# What is the "greenhouse effect"?

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## Overview

You know that putting on another layer of clothing helps keep you warm on a chilly day. The same is true for the earth — the layers of the atmosphere keep the earth at a higher temperature than it would otherwise be.

## Theory

If the earth was bare rock, with no atmosphere, like the moon, the average surface temperature would be approximately -18°C (about 0°F).

The earth is, of course, warmer than this — quite a bit warmer, as it turns out. The average surface temperature on the earth is approximately 15°C (about 60°F). The earth is kept warmer by its atmosphere; the mechanism by which this occurs is known as the greenhouse effect. It's easy to do a simple experiment that gives clues as to how the atmosphere works this magic. The key, just like the key to keeping warm in the winter, is layers.

If you take your warm hand and place it in a cup of cold water, heat will flow from your hand to the water. If you put your hand in a cup of hot water, heat will flow from the water to your hand. That's thermodynamics — specifically, the second law of thermodynamics: Heat flows from hot to cold. The rate at which heat flows depends on the temperature difference; heat flows more quickly if the temperature difference is large, more slowly if it is small. If you swim in a cool river, you'll get chilly after a while; if you swim in the Arctic Ocean, you will quickly get hypothermia.

This dependence on temperature difference is true for all mechanisms of heat exchange, including conduction (direct transfer by two objects in physical contact), convection (transport of fluids, like water or air), or radiation (transfer of energy by emission of electromagnetic waves.) The earth sits in the vacuum of space, so the only way it can gain or lose energy is by radiation. Understanding energy gain and loss by radiation helps us explain why the earth is warmer than it "should" be.

*Layers keep you warm by gradually "stepping down" the temperature between your body and the outside world. Adding more layers will decrease the temperature difference across each layer — each "step" will be smaller.*

The atmosphere above us has many layers, and their temperatures vary. The earth gets energy in the form of electromagnetic radiation from the sun, and it gives off energy, again as electromagnetic radiation, to space. But there's a difference in these two types of radiation. The wavelength of the electromagnetic waves that an object emits depends on the object's temperature. Higher temperature means shorter wavelength. The incoming radiation from the sun, with its 6000°C surface temperature, is mostly visible light. The visible light passes right through the atmosphere. The outgoing radiation from the surface of the earth, which has an average temperature of 15°C, is mostly longer-wavelength thermal radiation. Thermal radiation doesn't pass through the atmosphere so easily; much is absorbed and subsequently re-emitted, largely by water vapor and carbon dioxide. The direction in which the radiation is re-emitted is random; some travels toward space, and some travels toward Earth. The presence of these gases in the layers of our atmosphere thus keeps them — and therefore us — warmer.

## Doing the experiment

This lesson gives you a good excuse to teach outside — in the winter! You want your (warmly attired) students to be outside long enough that the temperatures of the layers of their clothes have equilibrated. This will take some time, at least 10-15 minutes. After this time, their garments will be warm on the inside, cool on the outside. You'll get the most interesting results from students wearing layers — a shirt, a sweater, and a thin jacket would be ideal. We'll assume this set of layers for the following description.

- Have one student with a good set of layered clothing serve as the test subject. Pick a spot in the middle of his back and use the thermal radiation sensor to measure the surface temperature of his jacket.
- Now, have him quickly remove his jacket, and measure the surface temperature of his sweater at the same spot.
- Next, have him quickly remove his sweater, and measure the surface temperature of his shirt at this spot.
- Finally, use the sensor to measure his skin temperature — ideally in the same spot, but use your judgement here. The inside of the forearm could work as well.

**Necessary materials:**

- thermal radiation sensor ("infrared thermometer")
- student with layers of jackets, sweaters, and other warm clothes
- cold day

It's important to get a thermal radiation sensor (this is a more accurate description of these instruments than the more common"infrared thermometer") that can measure very cold temperatures, and which has a reasonably narrow field of view. You can find such a device at www.harborfreight.com under "non-contact pocket thermometer."

Look at the range of temperatures, from the warm skin to the cool outside of the jacket. There is a big difference in temperature between the inside and the outside, but each layer sits next to another layer which is only slightly different in temperature. Ask your students to explain how this layering, this "stepped" temperature profile, will help them stay warm.

Now, do this:

- Aim the thermal radiation sensor at the sky. Space is quite cold — deep space is about -270°C, or -455°F. But the sensor measures a temperature that is much less frosty; it will probably read about 0°C, or perhaps as cool as -10°C or even -30°C. Cold, yes, but not -270°C! (It's important to note that what you measure isn't actually the temperature of the sky, for reasons explained below.)

What the sensor is measuring is the thermal radiation emitted of a layer of the atmosphere that absorbs the earth's emitted thermal radiation. This is, in general, how thermal radiation sensors work — they measure thermal radiation, and make some assumptions to calculate a temperature based on this measurement. This is why we prefer not to call them "infrared thermometers" — they're not really measuring temperature! The assumptions the device makes aren't accurate for the earth's atmosphere, so if you measure a sky temperature of -12°C, this just means that you're getting relatively little thermal radiation from the sky… But it's still more than you'd get from space! Because the earth is covered by a layer of atmosphere that is cooler than the earth but warmer than space, it keeps the earth warmer. After making both sets of measurements, you can help your students make this connection.

## Summing up

Now, for the obvious question: If the earth is kept warm by the atmosphere, and if carbon dioxide in the atmosphere is in no small part responsible for this warming, and if we as a species are increasing the level of carbon dioxide in the atmosphere, won't that cause the earth to warm up? The answer is: Almost certainly. It's like putting on another layer of clothing on a cold winter day, a simple matter of thermodynamics.

Of course, the atmosphere is more complicated than this; there might be other effects. But it is a fact that we are adding carbon dioxide to the air, and that the climate is changing. There is clear data to show both effects.

## For more information

Colorado State University College of Natural Sciences: http://www.natsci.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu