Overview

The physics of how the atmosphere works is quite simple; it can be described with some very straightforward equations. The behavior of the atmosphere itself, though, is quite complex, and certainly cannot be expressed in a series of simple equations. This is why we use models — tools that build up from the very simple concept of a physical theory to the complicated behavior of a real physical system. In this activity, students will run a basic model which uses the fundamental physics of radiation to describe energy exchange and temperature variation among several broad elements of the earth-atmosphere system.

Theory

Climate models start with physical theories: How air moves, how water behaves, how radiation transports energy. They then break the earth's atmosphere down into pieces (“cells”) and then compute what happens in each cell based on these physical theories. Cells exchange energy and matter with each other based on the physics of the transfer of matter and energy. The net result is a simulation of what the actual atmosphere might do. We can illustrate this idea by doing a very, very simple model for a piece of the atmosphere, as described below.

Doing the experiment

See detailed instructions below. Start with a simple simulation:

1) Have each element of the atmosphere start with tokens in the bold outlined squares—for example, the earth’s surface starts with 19 chips.
2) Now run the model for 4 turns. How do the temperatures change?
3) Now, continue the simulation — keep running it, and have students keep track of the temperatures.

At some point, the model will stabilize; all of the elements will remain at the same temperature for each turn. How long does it take to reach this point? This is the final temperature profile that the model predicts for the atmosphere. Just as in the real atmosphere, the earth’s surface is warmer than the lower atmosphere, and the temperature continues to drop as you go higher.

The model breaks down at the high end, though: In fact, the stratosphere is hotter than the lower atmosphere. That’s because the stratosphere is heated by the sun, something our model doesn’t consider. But we can fix this! You should try “tweaking” the model a bit to get a more realistic result. You could add another layer to the atmosphere, and then have space give some energy to the highest level each turn — say 3 tokens to earth and 1 token to the upper atmosphere. How does this alter the predicted temperature profile?

You could also do an open-ended discussion of how this model could be made more realistic. What elements would you add?

Setting the model up

You’ll need 4 people to run the model. Each person represents one component of the model: one person is the earth’s surface, one is the lower atmosphere, one is the upper atmosphere and one is space. The four people sit in a row, in order, just as the different segments appear in relation to each other:

Earth’s Surface  Lower Atmosphere  Upper Atmosphere  Space
Each element can exchange energy with the adjacent element:

- The earth’s surface exchanges energy with the lower atmosphere.
- The lower atmosphere exchanges energy with the earth’s surface and with the upper atmosphere.
- The upper atmosphere exchanges energy with the lower atmosphere and with space.
- Space exchanges energy with the upper atmosphere.
- In addition, the earth’s surface receives energy directly from the sun (space).

The amount of energy exchanged depends on the temperature: If an element is hotter, it emits more energy.

We’ve included two basic regimes for the model, Current Atmosphere and Elevated CO₂. Current Atmosphere is based on the amount of CO₂ in the atmosphere at the time you’re running the model, and Elevated CO₂ represents a higher amount of CO₂ in the atmosphere than the current levels. The models differ in the rate of energy exchange — true to the natural world, increasing CO₂ levels increases the rate of energy transfer among the elements of the atmosphere. Run the model first using the Current Atmosphere regime, then try the Elevated CO₂ regime to see the differences.

Running the model

During each “turn” each element exchanges energy with other elements using the transfer cups. The energy transferred depends on the temperature of each element.

Before beginning the model, the earth, lower atmosphere and upper atmosphere each get enough tokens (via the transfer cups) to place one in each bolded square on their Heat Exchange Model sheet (last 3 pages of this document). This represents a typical temperature distribution, and lets your students start to see trends more quickly than they would if they had to wait for this distribution to arise naturally in the model (though, given a bit of time, it does arise, which may be interesting for your students as well). The highest-temperature row containing tokens determines the amount of energy to be transferred.

During one “turn,” each element exchanges energy with other elements (sample numbers given for the Current Atmosphere regime):

- The earth’s surface exchanges energy with the lower atmosphere via a transfer cup. The amount transferred is determined by the temperature of the earth. If the temperature of the earth’s surface is in the 3rd bracket from the bottom, then 4 tokens are transferred to the lower atmosphere.
- The lower atmosphere exchanges energy with the earth and with the upper atmosphere. If the temperature of the lower atmosphere is in the 3rd bracket from the bottom, then 3 tokens are transferred to earth and 3 are transferred to the upper atmosphere.
- The upper atmosphere exchanges energy with the lower atmosphere and with space. If the temperature is in the lowest bracket, then 1 token is transferred to the lower atmosphere and 1 is transferred to space.
- Space holds all the extra tokens. Regardless of how many tokens it has, space gives 3 tokens to the earth’s surface during the daytime, because energy from the sun heats the earth directly.

Each element places the newly received tokens on their Heat Exchange Model sheet and notes changes to the temperature. The new temperature bracket determines the energy transferred to adjacent elements during the next “turn.”

Necessary materials:

- ~75 chips or tokens
- 5 small cups to transfer chips or tokens among the students running the model
- bowl to represent space
- one copy of each of the Heat Exchange Model sheets (at the end of this document)

Students will work in groups of four for this activity, one student representing each element in the model.
Take 4 turns of daylight, with the sun (space) transferring energy to the earth’s surface, and 4 turns of nighttime, with no transfer of energy from the sun (but the upper atmosphere still transfers energy to space). Repeat this cycle until you see the temperature of each element start to achieve relatively stable daytime and nighttime values. Then repeat the entire process using the rates of energy transfer corresponding to an atmosphere containing elevated levels of CO$_2$. (The rate at which the earth’s surface receives energy from the sun is not altered in this regime; greenhouse gases do not interact with short-wavelength radiation from the sun. They do, however, absorb and emit thermal radiation — such as that emitted by the surface of the earth — quite strongly.)

Make sure to pause throughout the model and encourage students to note the temperature changes they observe. There will be some quite interesting effects, and some in the Elevated CO$_2$ regime may require a bit of explanation. Students will likely observe that, under this regime, the earth’s surface warms dramatically and the upper atmosphere cools. The increase in CO$_2$ in the upper atmosphere allows this layer to radiate thermal energy more effectively, and thus maintain its energy balance at a lower temperature than typical, so its temperature decreases. Students will also likely note that energy exchange rates from the earth’s surface don’t change if CO$_2$ levels increase — atmospheric changes don’t affect the ability of the surface itself to transfer energy. However, they do result in increased rates of energy transfer to the earth’s surface from the lower atmosphere. Raising energy input without raising energy output results in an increase in the earth’s surface temperature. Both results mentioned here — increasing temperatures at the earth’s surface and falling temperatures in the upper atmosphere — have been clearly measured as anthropogenic CO$_2$ emissions continue to rise.

**Summing up**

This is a very simple model, but it captures the key elements of what a model is and does, and it offers an opportunity to add complexity.

**For more information**

Colorado State University College of Natural Sciences: [http://www.natsci.colostate.edu](http://www.natsci.colostate.edu)

Little Shop of Physics: [http://littleshop.physics.colostate.edu](http://littleshop.physics.colostate.edu)
Earth’s Surface

Current Atmosphere or Elevated CO$_2$

- transfer 7 chips
- transfer 6 chips
- transfer 5 chips
- transfer 4 chips
- transfer 3 chips
- transfer 2 chips
Lower Atmosphere

Current Atmosphere
- transfer 6 chips

Elevated CO₂
- transfer 7 chips

more chips → higher temperature

TRANSFER to upper atmosphere

TRANSFER to Earth’s surface
Upper Atmosphere

More chips → higher temperature

Current Atmosphere

- Transfer 6 chips
- Transfer 5 chips
- Transfer 4 chips
- Transfer 3 chips
- Transfer 2 chips
- Transfer 1 chip

Elevated CO₂

- Transfer 7 chips
- Transfer 6 chips
- Transfer 5 chips
- Transfer 4 chips
- Transfer 3 chips
- Transfer 2 chips