

## FOLLOW THE ENERGY! EARTH'S DYNAMIC CLIMATE SYSTEM

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**Driving Question:** *How does energy enter, flow through, and exit Earth's climate system?*

**Educational Outcomes:** To consider Earth's climate as an energy-driven physical system. To investigate fundamental concepts embodied in considering Earth's climate from a dynamic perspective and through the use of models.

**Objectives:** The flow of energy from space to Earth and from Earth to space set the stage for climate, climate variability, and climate change. After completing this investigation, you should be able to describe fundamental understandings concerning:

- The global-scale flow of energy between Earth and space.
- The impact of the atmosphere on the flow of energy to space.
- The effect of incoming solar radiation on Earth's energy budget.
- The likely effects of energy concentrations and flows on Earth system temperatures.

### Earth's Dynamic Climate System

Earth's climate is a dynamic energy-driven system. **The radiant energy received from space and that lost to space on a global basis determine whether or not Earth is in a steady-state condition, cooling, or warming.** An unchanging balance between incoming and outgoing radiation produces a steady-state and stable climate. Lack of a balance between incoming and outgoing radiation implies a net loss or gain of radiant energy to Earth's climate system. **One result of such an energy imbalance is climate change.**

Earth's climate evolves under the influence of its own internal dynamics and because of changes in external factors that perturb the planet's energy balance with surrounding space. **The three fundamental ways in which this energy balance can be disturbed** are by changes in the amount of:

1. solar radiation reaching the Earth system;
2. incoming solar radiation that is absorbed by the Earth system; and,
3. infrared (heat) radiation emitted by the Earth system to space.

Solar radiation intercepted and absorbed by Earth drives our planet's climate system. Earth responds to this acquired energy through the emission of long-wave infrared (heat) radiation as its climate system adjusts towards achieving global radiative equilibrium with space. Because the amount of solar energy intercepted by Earth can be determined with great accuracy by instruments onboard Earth-orbiting satellites, the stage is set for the development of climate models with the potential of predicting future states of Earth's global-scale climate system. In addition to predicting future climate, these climate models can be manipulated quantitatively (e.g., changing the atmospheric concentrations of heat-trapping gases) to

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provide insight into the probable consequences of various human activities (e.g., combustion of fossil fuels, land clearing).

In this course, the *AMS Conceptual Energy Model* (AMS CEM) will be employed to investigate basic concepts underlying the global-scale flows of energy to and from Earth.

This investigation explores energy flow in a highly simplified representation of an imaginary planet and the space environment above it. The purpose is to provide insight into the impacts of physical processes that operate in the real world. This investigation follows the flow of energy as it enters, resides in, and exits a planetary system model, as shown in **Figure 1**. As seen in Figure 1 (a), short-wave solar energy is intercepted by the planet and absorbed at its surface. In Figure 1 (b), the solar-heated surface emits long-wave infrared radiation upwards. In the absence of an atmosphere, the upward-directed radiation would immediately be lost to space. With a particle-free (e.g., no clouds) atmosphere added to the planet, as in Figure 1 (c), some of the upward-directed radiating energy would be absorbed by molecules of heat-trapping greenhouse gases (primarily  $\text{H}_2\text{O}$  and  $\text{CO}_2$ ). **The absorbed energy subsequently radiates from the molecules to their surroundings randomly in all directions, with essentially half of the emissions exhibiting a downward component and half an upward component.** While upward emissions can escape to space, the energy directed downward can return to the planet's surface and add to the amount of energy contained in the planetary climate system.

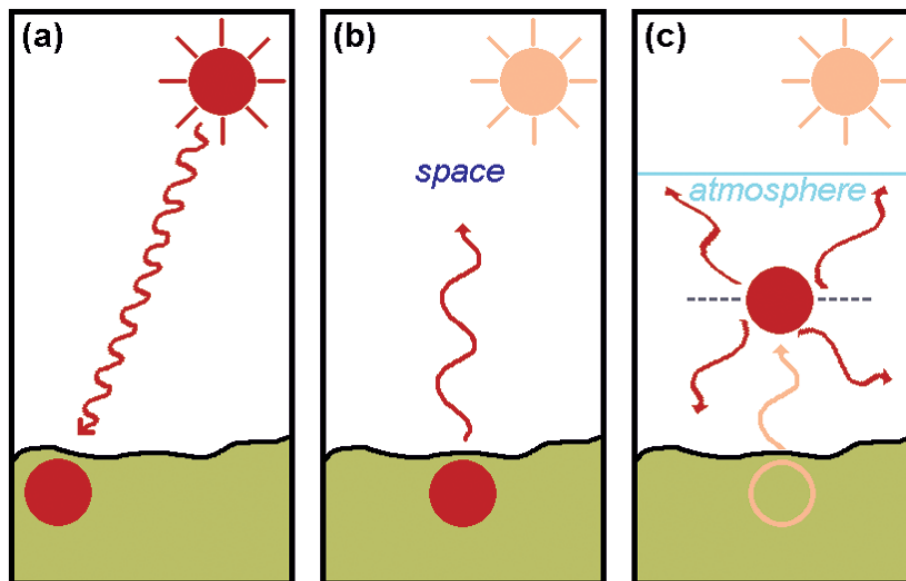


Figure 1.

(a) Sunlight heats the surface of the planet. (b) In absence of an atmosphere, the surface emits infrared radiation to space. (c) If there is an atmosphere, greenhouse gases absorb infrared radiation emitted from the planet's surface and then radiate the energy in all directions, with half directed downward and half upward.

## Starting the AMS CEM Investigation:

The *AMS Conceptual Energy Model* (AMS CEM) is a computer simulation designed to enable you to track the paths that units of energy might follow as they enter, move through, and exit an imaginary planetary system according to simple rules applied to different scenarios. For simplicity, consider *units of energy* to be equivalent bundles or parcels of energy. To access the interactive model, go to the course website and in the “Extras” section, click on [AMS Conceptual Energy Model](#).

As shown in **Figure 2**, the AMS CEM is presented as a landscape view of a planetary surface, with the Sun depicted in the upper right corner. The AMS CEM is manipulated by choosing different combinations of conditions via windows along the top of the view. Once the conditions have been set, click **Run** to activate the AMS CEM.

Become acquainted with the AMS CEM. Start by selecting “One Atmosphere” under **Atmospheres** and “Energy: 100%” (denoting the arrival of a fresh unit of energy from the Sun during each cycle of play) under **Sun’s Energy**. Select “10 cycles” under **Cycles** so a model run will be composed of 10 cycles of play. Select “Introductory” under **Mode**. Finally, click on **Run**. Because the model is in the Introductory mode, you can observe the same run repeatedly without the cycle patterns changing. You can also stop a run at any time by clicking on **Pause** in the Run window, and then continue the run by clicking on **Resume** in the same window. Note that each model run starts with one unit of energy already at the

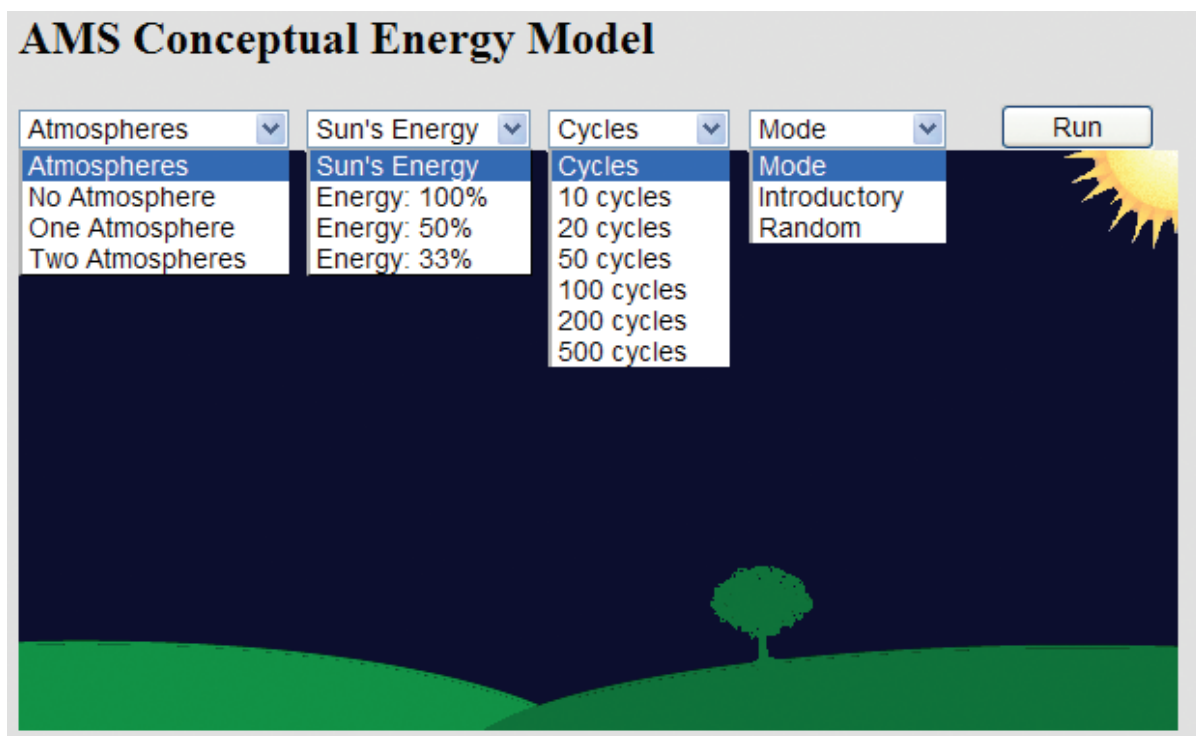


Figure 2.  
Landscape view of AMS CEM showing possible choices or settings to conduct model runs.

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planet's surface. An atmosphere, if present, does not absorb any of the incoming sunlight passing through it.

1. Repeating or stepping through the run specified above as many times as necessary, follow the first energy unit that originated from the Sun. As it arrives at the planet's surface, the yellow energy unit changes to **[(green)(blue)(red)]**. This signifies its transition from sunlight to heat energy as it is absorbed into the planet's climate system.

In the AMS CEM, a *cycle of play* refers to a sequence of moves in which every energy unit in the planet system is subjected to one vertical move. A model *run* is composed of a specified number of cycles of play (i.e., 10, 50, 200). For example, a 10-cycle run of the model indicates that whatever energy there is in the planetary climate system at the beginning of each of the 10 cycles of play is subjected to one vertical-motion play during the individual cycle.

Once an energy unit is in the planet system, the **two rules to be followed** as it flows through the planet system during each run of the AMS CEM are as follows:

**Rule 1.** During each cycle of play, any energy unit at the planet's surface will have an equal chance of staying at the planet's surface or moving upward.

**Rule 2.** During each cycle, any energy unit in the atmosphere will have an equal chance of moving downward or upward.

These rules are primarily based on the fact that regardless the direction an energy unit comes from when it is absorbed by an atmospheric molecule (i.e., CO<sub>2</sub>, H<sub>2</sub>O), the gas molecule can emit the energy in any direction. Half the emitted radiation will have a downward component, and half an upward component.

2. Once an energy unit has been absorbed into the planet system, it continues to play every remaining cycle in the run until it is either lost to space or is retained somewhere in the planet system. Continue to follow the first energy unit that arrived from the Sun by replaying the run as many times as you wish, or, by stepping through the run by alternately clicking on **Pause** and **Resume**. In the cycle immediately following its absorption at the planet's surface, the energy unit being tracked **[(stays at the planet's surface)(moves up to the atmosphere)]**.
3. In its next play, the same energy unit **[(moves up to space)(moves down to planet's surface)]**.
4. Follow the same energy through the subsequent cycles of play. By the end of the 10-cycle run, it **[(remains in the planet system)(was lost to space)]**.
5. Next, follow the second energy unit to arrive from the Sun. After two cycles of play, it ends up **[(at planet's surface)(in the atmosphere)(in space)]**.

6. The planet's climate system in the AMS CEM includes the planet's surface and any existing atmosphere. This *Planet with an Atmosphere* computer simulation, as with all AMS CEM simulations, starts with one energy unit in the planet system at the planet's surface. After its 10 cycles of play, this particular run shows the planet system (surface and atmosphere) ending up with [~~1~~]~~(2)~~~~(4)~~~~(6)~~] units of energy.

Running this and other simulations in the Introductory Mode always produces the same results for the individual simulation. This is because in the Introductory Mode all energy unit movements are determined by the same set of random numbers essentially “frozen” for the purposes of demonstrating how the model works. Random numbers are employed in AMS CEM to assure that energy-unit movements are determined purely by chance. [In the Random Mode a unique sequence of random numbers is generated with every run, so no two runs can be exactly alike and no run can be repeated.]

7. Modify the Mode setting for the AMS CEM simulation you have been examining (One Atmosphere, Energy: 100%, 10 cycles) by clicking on “Random” under the Mode heading. Now click on the Run button, and watch the model go through its 10-cycle run. Play the new simulation several times, looking for similarities and/or differences. With the random setting, different runs of the model produce [~~(different)~~]~~(the same)~~] results.

The AMS CEM allows you to investigate numerous questions, such as what impact does an atmosphere have on the amount of energy residing in the system. You can explore this question by modifying the settings of the AMS CEM. Select “No Atmosphere”. The other settings remain: Energy: 100%, 10 cycles, Random mode.

8. You have now changed the AMS CEM to evaluate a computer simulation of a *Planet with no Atmosphere*. Click on the Run button and watch the model go through its 10-cycle run. Repeat several times. Comparison of several runs of the simulations with and without an atmosphere, reveals the generalization that more energy is retained in the planet system that [~~(has)~~]~~(does not have)~~] an atmosphere.
9. Stated another way, comparing the two simulations (with and without an atmosphere) shows that the addition of an atmosphere, containing energy-absorbing molecules, causes the amount of energy in the planet's climate system to [~~(increase)~~]~~(remain the same)~~ ~~(decrease)~~].

Now change the AMS CEM setting to: One Atmosphere, Energy: 100%, 10 cycles, and Introductory mode. Click on the Run button to review the 10-cycle run. Then, sequentially, choose and make “20”, “50”, and “100” cycle runs. Since the model is running in the Introductory mode, each subsequent higher-cycle run embodies the previous lower-cycle runs. Note that the model speeds up as the number of cycles in a run increases. This is primarily done as a time-saving device when operating the AMS CEM.

Set the model to 200 cycles and click on the Run button. While it is running, note the curves being drawn on the graph directly below the landscape view. This part of the model is

reporting (blue curve) the number of energy units in the planet system cycle-by-cycle as the run progresses. It is also reporting a five-cycle **running average** (green curve). Running averages are commonly calculated in climate science to even out short-term variations and reveal trends. They are calculated at the end of each cycle by adding the most recent observed value and dropping the oldest one. This averaging technique is especially useful the environmental sciences as new observational data are collected.

10. Directly above the graph, the model reports that for the 200-cycle run, the mean (average) number of energy units in the planet system after each cycle was [~~(3.0)~~~~(4.7)~~~~(6.6)~~~~(8.2)~~].

The model starts a run with one energy unit in the planet system and the arrival of one energy unit from the Sun. An initial “**spin up**” of the model occurs over ten to twenty cycles before it appears to suggest the model has achieved a relatively stable condition. Although the numbers of energy units in the planetary system can vary considerably over several cycles, the long-term trend shows little evidence of either increasing or decreasing.

11. After an initial “spin up” of the model, the number of energy units in the planet system during the 200-cycle run ranged between [~~(0)~~~~(1)~~~~(3)~~~~(5)~~] and 8.

12. After the spin-up phase, the overall pattern of the energy-content curve exhibits **natural variability** because the model settings are the same throughout the 200-cycle run. At the same time, the overall pattern of the curve suggests that the planet’s climate system (i.e., energy content) appears relatively steady. Assuming such a “**steady state**” condition was achieved, it can be expected that the rate at which energy is leaving the system to space would be [~~(less than)~~~~(equal to)~~~~(more than)~~] the rate of incoming energy from space.

We will return to the AMS CEM in future investigations to follow the flow of energy through Earth’s climate system in different simulations under different sets of conditions.

## Earth’s Climate System Models

The purpose of the AMS CEM is to provide a tool enabling you to explore fundamental aspects concerning energy flow to, through, and from Earth’s climate system. Climate system models for scientific research and prediction are much more complex. They are mathematical computer-based expressions of the conversions between heat and other forms of energy, fluid motions, chemical reactions, and radiant energy transfer.

The use of models to predict weather and investigate the Earth system and its climate system was one of the most immediate results of the invention of the computer and rapid development of computer technology beginning in the 1950s. NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton University created during the 1960s and 1970s what was generally recognized as the first true Global Circulation Model (GCM) that represented large scale atmospheric flow. It was at GFDL that the first climate change carbon-dioxide doubling experiments with GCMs were conducted. In 1988, a NASA report (*Earth System Science: A Closer View*) led by Francis Bretherton (University of Wisconsin-

Madison) called for an ambitious research program that integrated studies of Earth's atmosphere, hydrosphere (ocean, ice), geosphere (land), and biosphere and the interactions over different time and space scales. The NASA report provided the scientific and conceptual framework for many national and international research programs, including the development and use of computer climate models.

**Figure 3**, now often referred to as the *Bretherton Diagram* (in its simplified version), conceptually described Earth system components (or sub-systems) that would need to be considered in advanced computer climate models.

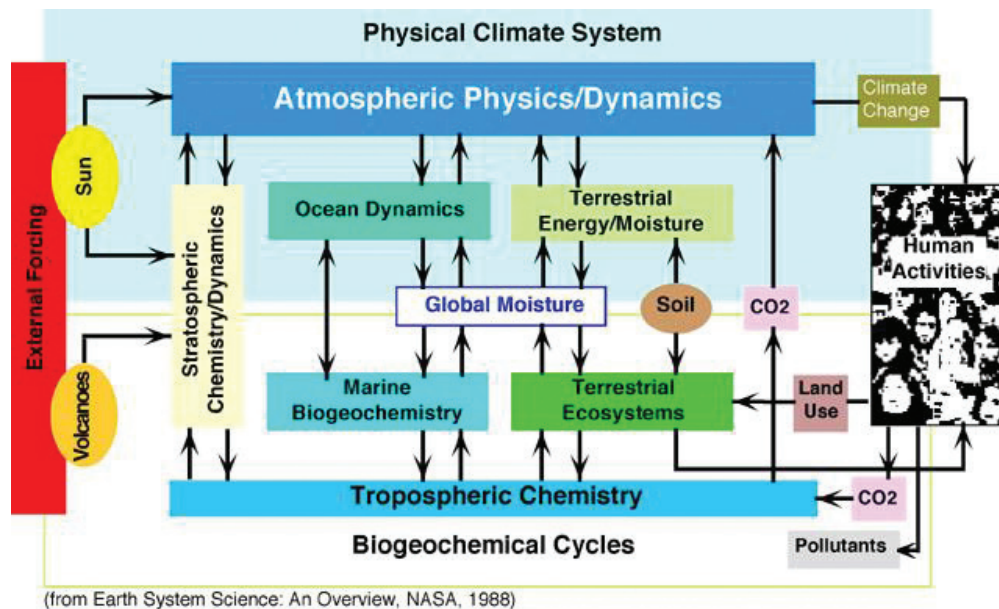


Figure 3.

A simplified version of the Bretherton Diagram describing connections between sub-systems of Earth's climate system.

13. The Bretherton Diagram indicates that the products of human activities impacting the Earth (climate) system include **[(pollutants)(CO<sub>2</sub>)(land use)(all of these)]**.
14. The diagram identifies **[(the Sun)(global moisture)(soil)]** as an external forcing on the Earth system.

**Summary:** This Investigation has presented the AMS CEM, a simple conceptual model that demonstrates climate as a planet system's response to external forcing (radiant energy from the Sun) and the amount of energy that is held in the system. It embodies some basic elements of the Bretherton Diagram and computer-based climate models which are representations of the climate system based on the mathematical equations governing the behavior of the various components of the system, including treatments of key physical processes, interactions, and feedback phenomena.

## EdGCM Project:

Computer-driven global climate models (GCMs) are prime tools used in climate research. The Educational Global Climate Modeling Project provides a research-grade GCM, called **EdGCM**, with a user-friendly interface that can be run on a desktop computer. Educators and students can employ EdGCM to explore the subject of climate change the way research scientists do. The model at the core of the EdGCM is based on NASA's Goddard Institute for Space Studies GCMs. To learn more about EdGCM, go to: <http://edgcm.columbia.edu/>.

**Please note that the Internet addresses appearing in this Investigations Manual can be accessed via the "Learning Files" section of the course website. Click on "Investigations Manual Web Addresses." Then, go to the appropriate investigation and click on the address link. We recommend this approach for its convenience. It also enables AMS to update any website addresses that were changed after this Investigations Manual was prepared.**