Objectives

The flows 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 lost to space on a global basis determines whether Earth is in a steady-state condition, cooling, or warming. A balance between incoming and outgoing radiation produces a steady-state and stable global 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. As stated by the Inter-governmental Panel on Climate Change, Working Group 1, 5th Assessment Report (IPCC, WG1-AR5), “Changes in the global energy budget derive from either changes in the net incoming solar radiation or changes in the outgoing longwave radiation.” Thus, there are three fundamental ways in which the radiation balance of the Earth can be changed:

1) Change in the incoming solar radiation (e.g., changes in Earth’s orbit or Sun’s output);
2) Change in the fraction of solar radiation that is reflected (called ‘albedo’; e.g., by changes in cloud cover, atmospheric particles or surface conditions such as vegetation);
3) Alteration of the longwave radiation from Earth towards space (e.g., by changing atmospheric composition, especially greenhouse gas concentrations).

Climate responds directly to these changes, and indirectly through numerous feedback mechanisms.

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 radiation (IR) as its climate system adjusts toward achieving global radiative equilibrium with space. Because the amounts of solar energy intercepted by Earth and the IR emitted to space 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 provide insight into the probable consequences of various human activities (e.g., combustion of fossil fuels, land clearing).

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

The AMS CCEM enables the user to explore 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 1a, short-wave solar energy is intercepted by a planet with no atmosphere and absorbed at its surface. In Figure 1b, the solar-heated surface emits long-wave infrared radiation upwards. In the absence of an atmosphere, the upward-directed radiation is immediately lost to space. With a clear, cloud-free atmosphere added to the planet, as in Figure 1c, some of the upward-directed radiating energy is absorbed by molecules of heat-trapping greenhouse gases (primarily H₂O and CO₂). The absorbed energy subsequently radiates from these atmospheric molecules to their surroundings randomly in all directions, with 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 increase the amount of energy contained in the planetary climate system, resulting in a warmer planet.

![Figure 1](image.png)

**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 AMS CCEM Investigations

The AMS CCEM 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. As shown in Figure 2, the AMS CCEM is presented as a landscape view of a planetary surface, with the Sun depicted in the upper right corner. The AMS CCEM is manipulated by choosing different combinations of conditions via drop-down menus along the top of the view. Once the conditions have been set, the model is activated by the user.

![AMS Conceptual Climate Energy Model](image)

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

To access the interactive model, go to the AMS Conceptual Climate Energy Model (AMS CCEM) welcome page and click on “Run the CCEM Model” link. You can also access the model through the Real Time Climate Portal Maps & Links page; Extras; “AMS Conceptual Climate Energy Model”.

The AMS CCEM is already loaded with default settings, seen color-coded blue in Figure 2, as an introduction. They are “100%” under Sun’s Energy (denoting the arrival of a fresh unit of energy from the Sun during each cycle of play), “0%” for Albedo (indicating the percentage of incoming sunlight being directly reflected or scattered back towards space), and “Current (1x)” under Atmospheric CO₂ (current concentration of CO₂ in the atmosphere). The values of “1 unit” under Initial Energy (energy residing in the model at the beginning of the model run) and “20 cycles” under Cycles stipulates a model run composed of 20 cycles of play. “Introductory” has been selected under Mode. Finally, click on the “Run” button. Because the model is in the Introductory mode, you can observe the same run repeatedly without the cycle patterns changing. You can stop a run at any time by clicking on “Pause,” and then continue the run by clicking on “Resume.” To return the CCEM to its original default settings, click on your
browser’s refresh/recycle icon.

Note that each new model run starts with the number of units of energy already at the planet’s surface indicated. The atmosphere does not absorb or scatter any of the incoming sunlight passing through it when the Albedo setting is 0%. A 0% albedo in this model indicates that all of the Sun’s energy entering the planetary system arrives at the planet’s surface and is totally absorbed.

1. Repeat or step through the run specified above (in the Introductory Mode) as many times as necessary to track the first energy unit that originated from the Sun. As it arrives at the planet’s surface, the yellow energy unit changes to ________. This signifies its transition from sunlight to heat energy as it is absorbed into the planet’s climate system.

   a. green
   b. blue
   c. red

In the AMS CCEM, a cycle of play refers to a sequence of moves in which every energy unit in the planet system is subjected to the possibility of one vertical move. A model run is composed of a specified number of cycles of play (i.e., 20, 100). For example, a 20-cycle run indicates that the energy in the planetary climate system at the beginning of each of the 20 cycles of play is subjected to one play during the individual cycle.

Once an energy unit is in the planet system, three rules govern its stepwise flow through the planet system during each run of the AMS CCEM:

**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 escaping upward.

**Rule 2.** Energy units leaving the planet’s surface as infrared (IR) radiation will be absorbed in the atmosphere if it contains IR-absorbing molecules (e.g., CO$_2$). If not (atmospheric CO$_2$ set as None), the energy units will escape directly to space.

**Rule 3.** During each cycle, any energy unit residing in the atmosphere will have an equal chance of moving downward or upward.

These rules are primarily based on the fact that regardless of the original direction from which an IR energy unit comes when it is absorbed by a radiatively-active atmospheric molecule (e.g., CO$_2$), the energy emitted from the gas molecule can radiate in any direction. Consequently, half the emitted radiation will be directed downward, and half will be directed upward.

2. An energy unit absorbed into the planet system turns red, signifying its change to heat energy. It remains red when radiated to indicate infrared (IR) radiation is emitted. It continues to be in play in every remaining cycle in the run until it is lost to space. Follow the same first energy unit that arrived from the Sun. In the cycle immediately following its initial absorption at the planet’s surface, the energy unit ________. [You can replay the run as many times as you wish, and you can step through individual runs by alternately clicking on “Pause” and “Resume.”]

   a. stays at the planet’s surface
   b. moves up to the atmosphere
3. Eventually, the same energy unit ________.
   a. moves up into the atmosphere
   b. moves directly from the planet’s surface to space

4. The planet’s climate system in the AMS CCEM includes the surface and any existing atmosphere. Follow the same first energy unit from the Sun through the 20 cycles. By the end of the 20-cycle run, it ________.
   a. is still in the planet system
   b. had been lost to space

5. The default setting shows a planet having a concentration of atmospheric CO$_2$ equivalent to the current Earth value and an initial energy content of 1 unit. After 20 cycles of play, this model run shows the planet system (surface and atmosphere) ends up with ________ energy units. Sometimes squares representing energy units can overlap, so verify your answer by checking the graph value at the end of the 20$^{th}$ cycle.
   a. 2
   b. 4
   c. 6
   d. 8

Running this and other simulations in the model’s Introductory Mode always produces the same result from the same model setting. This is because in the Introductory Mode all energy unit movements are determined by a fixed set of “random numbers” essentially frozen for the purposes of demonstrating how the model works. Random numbers are employed in AMS CCEM to assure that energy-unit movements are determined purely by chance. [In the model’s Random Mode a unique sequence of random numbers is generated with every run, so it is extremely unlikely any two runs will be exactly alike.]

6. We introduced the AMS CCEM in 20-cycle runs to see what happens in slow motion. Now change the number of cycles to “50” while keeping the other default settings, including the Introductory Mode. This increases the length of the run as well as speeding up the model. Click on “Run” and watch the model operate, noting that after 50 cycles there are 5 energy units left in the planet’s climate system (3 in the surface and 2 in the atmosphere). Now, change the model from the Introductory Mode to Random Mode, and run the model several times. With the Random Mode setting, different runs of the model produce ________ results in terms of the numbers of energy units residing in the surface and atmospheric components of the planet system at different times during an individual run and often at the end of the model run.
   a. different
   b. the same

The AMS CCEM allows you to investigate numerous questions, such as, “What impact does atmospheric CO$_2$ have on the amount of energy retained in the system?” You can explore this question by starting with the default settings except for setting Cycles to “100” and changing the Atmospheric CO$_2$ value to “None” (and be sure the Mode is “Introductory”).
7. You have now changed the AMS CCEM to evaluate a computer simulation of a planet with no radiatively active gas (e.g., CO\textsubscript{2}) in its atmosphere. Click on “Run” and watch the model go through a 100-cycle run. Next, change the Mode to “Random” and make several model runs. Compare the results with those of your earlier 50-cycle runs when the Atmospheric CO\textsubscript{2} setting was set at “Current (1x).” Comparison of several runs of the simulations with and without atmospheric CO\textsubscript{2}, reveals the generalization that more energy is retained in the planet system that ________ atmospheric CO\textsubscript{2}.

   a. has
   b. does not have

8. Stated another way, comparing the two simulations (with and without atmospheric CO\textsubscript{2}) shows that the addition of IR-absorbing atmospheric molecules, causes the amount of energy retained in the planet’s climate system to ________. Congratulations, you have just modeled the fundamental physical basis of the greenhouse effect.

   a. increase
   b. remain the same
   c. decrease

Below the AMS CCEM landscape view is a graph that displays the amount of energy in the planetary system after each cycle. With the AMS CCEM settings at: 100% Sun’s Energy, 0% Albedo, Current (1x) Atmospheric CO\textsubscript{2}, 1 unit Initial Energy, 20 Cycles, and Introductory Mode, click on the Run button to review the 20-cycle run. Then, run the model after sequentially choosing “50” and “100” cycles. Since the model is running in the Introductory Mode, each subsequent higher-cycle run embodies the previous lower-cycle runs.

Now set the model to 200 cycles in the Introductory Mode, and click on “Run.” While it is running, note the curve being drawn on the graph directly below the landscape view. This part of the model is reporting the number of energy units in the planet system cycle-by-cycle as the run progresses. This, in effect, reports the variability in the state of the planetary climate system. Also, for runs of 100 cycles or more, a mean value of energy units in the system at the end of each cycle and the standard deviation of the number of units is shown above the graph. The mean and standard deviation are only calculated from the number of units beyond the initial 50 cycles to avoid the fluctuations imposed by the choice of initial energy value. Extensive experience with the model shows an initial “spin up” occurs over ten to twenty cycles before it appears to suggest the model has achieved a relatively stable operating condition.

9. 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 beyond the initial 50 cycles was ________.

   a. 3.0
   b. 4.3
   c. 5.3
   d. 7.2
10. After the initial 50-cycle “spin up” of the model, according to the graphed data, the number of energy units in the planet system during the Introductory-mode 200-cycle run ranged between ________ and 9.

a. 0  
b. 1  
c. 2  
d. 3

11. Even with the model settings being the same throughout the 200-cycle run, the energy-content curve displays variability about the mean. The overall pattern of the curve suggests that the planet’s climate system (i.e., energy content) appears relatively stable. 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 ________ the rate of incoming energy from space.

a. less than  
b. equal to  
c. more than

Keeping other settings the same, switch to the Random mode. Try several runs of the model to see differences and similarities in the results. Since the settings were kept the same, the differences you observe, that is, differences in the means and departures from the means, must be due exclusively to chance within the model’s operation. These are examples of variability, the fluctuations above and below the long-term means of the data sets. They cannot be attributed to any change in the system settings (because there were no changes). That is, they were due to the inherent randomness built into the rules on which the model is based and any internal feedbacks that might exist.

We will return to the AMS CCEM in future investigations to follow the flow of energy through Earth’s climate system in different simulations under different sets of conditions. We will then use the model to objectively evaluate evidence of climate change.

**Earth’s Climate System Models**

The purpose of the AMS CCEM 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.

**Figure 3** schematically depicts the components, or sub-systems, of Earth’s climate system (atmosphere, ocean, terrestrial and marine biospheres, cryosphere, and land surface) that must be considered in advanced computer climate models. These major components interact with each other through flows of
energy in various forms, exchanges of water, the transfer of greenhouse gases (e.g., carbon dioxide, methane), and the cycling of nutrients. Solar energy is the originating source of the driving force for the motion of the atmosphere and ocean, heat transport, cycling of water, and biological activity.

Figure 3. Schematic view of the components of Earth’s climate system, their processes and interactions. [IPCC AR4 WG1, faq-1-2-fig-1]

12. The arrows in the figure identify the processes and interactions with and between the major components of Earth’s climate system. The double-headed arrows show that ________ of the processes and interactions between climate system components (e.g., precipitation-evaporation, land-atmosphere) involve bi-directional (upward/downward) flows.

a. few
b. about half
c. almost all
13. Six of the interactions depicted in Figure 3 are specifically labeled “Changes in ….” “Changes” imply forcing that results in climate change. While the human impact that most affects global climate is *Changes in the Atmosphere*, the human impact that is likely to be most directly observable in altering the local or regional climate is the one concerning the changes in the ________.

a. cryosphere  
b. hydrological cycle  
c. land surface  
d. ocean

**Summary**

This investigation has presented the AMS CCEM, 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 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.