Climate Science

1. Modern Climate Science / Follow the Energy!

ACCESSING AND INTERPRETING CLIMATE DATA

Background:

Our understanding of the climate system and climate variability depends on the quantitative measurement of a variety of atmospheric characteristics. These characteristics, which are often called "weather elements", include temperature, precipitation, humidity, air pressure, cloud cover, visibility, and wind speed and direction from locations around the world. Whereas some rudimentary weather instruments have been available for more than two centuries, detailed quantitative observations of the atmosphere did not commence until the mid to late 19^{th} century. When compiled, these data become climate data that can be used to help establish how the planetary climate has varied during the *instrumental era*, roughly spanning the past 130 years.

Detailed instrumental weather records have been collected and compiled in this country at many stations for more than a century. The National Weather Service (NWS) and its predecessor, the U.S. Weather Bureau, have operated a network of weather observation stations and offices in or near many of the large cities in every state, commonwealth, and territory under its jurisdiction. At many of these nearly 300 "first-order stations," systematic measurements of numerous weather elements are made by professional observers. Some of these weather data are recorded hourly, whereas other data are recorded once a day at some fixed time. An additional cooperative observer network of approximately 8000 volunteer observers provides daily readings of a limited selection of weather elements such as daily temperature extremes, 24-hr precipitation totals, and snowfall/snow depth. Some of these stations also make observations of evaporation, soil temperature, and peak wind gusts.

Essentially all meteorological data collected in the United States by government-sponsored observation networks are stored in archival form by the National Climatic Data Center (NCDC) in Asheville, NC. NCDC publishes *Local Climatological Data* for individual first-order stations and *Climatological Data* arranged by state. Copies of these publications are available at selected local libraries or resource centers; they are also available for free from the NCDC website. You may access some of these climate data through the link to US Climatology on the *Ann Arbor Earth Science Climate Studies Website*. More recent climatological data can also be obtained from the "Climatology" or "Climate" section of the web page maintained by essentially all of the National Weather Service Forecast Offices. Using the interactive map locate the desired NWS Office and go to the Local Climate section once their homepage appears on the screen; a link to this climate section can be located in the column on the left of the homepage. Nearly all of these NWS stations maintain *Preliminary Climatological Data* (or "CF6", formerly "F-6") for the current month on the Internet for the first-order stations in their area of responsibility. These data are updated daily and appear on the "Observed Weather Reports" section of the Climate page.

Climate data for selected cooperative observer stations in the NWS office's area of responsibility are also available in the section of the Climate Page identified with a tab titled "NOWData" (NOAA Online Weather Data). Daily temperature extremes, 24-hr precipitation totals and snow data are available for the last two months.

WHAT IS RECORDED

Whereas a variety of weather information is collected at essentially all types of weather observing stations, the following list pertains to the summary of the day weather data collected at first-order stations and presented in the monthly climate summaries (such as that found on the "CF6" form):

- DAILY MAXIMUM TEMPERATURE -- The highest temperature recorded by a sheltered registering thermometer during a calendar day defined as midnight to midnight local standard time.
- DAILY MINIMUM TEMPERATURE -- The lowest temperature recorded during a calendar day.
- DAILY AVERAGE TEMPERATURE -- The arithmetic average of the observed maximum and minimum temperature for the calendar day.
- 24-HOUR ACCUMULATED (liquid equivalent) PRECIPITATION -- The total depth of daily rainfall and melted frozen precipitation accumulated in a gauge during a calendar day.
- 24-HOUR ACCUMULATED SNOWFALL -- The total depth of the snow that fell during a calendar day; the snow depth is measured on a snowboard.
- SNOW COVER -- The average depth of accumulated snow on the ground measured at several representative points in the immediate area at a fixed observation time. Note that some stations may also include the water equivalent of the snow cover, obtained by melting a core of snow that has been collected.
- HEATING DEGREE-DAYS (65 degrees F base) -- The arithmetic difference between the daily average temperature and the base temperature of 65 degrees Fahrenheit. One heating degree-day is given for each degree that the daily average temperature departs below this base temperature.
- COOLING DEGREE-DAYS (65 degrees F base) -- The arithmetic difference between the daily average temperature and the base temperature of 65 degrees Fahrenheit. One cooling degree-day is given for each degree that the daily average temperature departs above this base temperature.
- RESULTANT WIND SPEED AND DIRECTION -- The vector sum of the hourly wind vectors (speed and direction) divided by the number of observations, specified in terms of a resultant speed (in mph) and a resultant direction taken (in degrees) with respect to true north (e.g., 90=east wind and 360=north wind).
- AVERAGE WIND SPEED -- The arithmetic average of the 24 hourly wind speed observations.
- PEAK or MAXIMUM WIND SPEED and DIRECTION -- The maximum observed wind speed and the direction for a 5-second or 2-minute time interval during the day.
- OTHER INFORMATION -- Some of the publications or sites include the following additional information in their monthly summaries:
- Departures from Normal -- The arithmetic difference between the daily average temperature and the long-term average daily temperature.
- Average Dewpoint and Average Wet Bulb Temperature -- The arithmetic average of the 24-hourly observed dewpoint and wet-bulb temperature for the calendar day.
- Weather -- Those significant weather phenomena observed during the calendar day such as thunder, rain, snow, fog, smoke or tornadoes.
- Sunshine Data -- Before October 2009, some stations that had sunshine recorders used to report the observed *Minutes of Bright Sunshine* and the *Percent Possible Sunshine*, or the ratio of the observed minutes of bright sunshine during the day to the elapsed time between local sunrise

and sunset. At the present time, no replacement to this sunshine recorder network is contemplated.

- Monthly tally of selected days that exceed certain thresholds -- The number of days during the month that are considered "rain days" when measurable rain (0.01 in. or greater) has fallen; "snow days" when snow (0.1 in. or greater) has fallen; and the number of days that the daily maximum and minimum temperatures have been above or below selected temperature thresholds (generally, 0 degrees, 32 degrees, and 90 degrees Fahrenheit).

Monthly summaries also include the monthly means of maximum and minimum temperature, determined from averaging the respective daily temperature extremes for each day in the month, as well as the average monthly temperature, representing the arithmetic average of the monthly average maximum and minimum temperatures. Monthly precipitation and snowfall totals represent the sum of the daily precipitation/snowfall totals in the month. Monthly totals of heating and cooling degree-days are also included which represent the sum of the daily number of degree-days in the month. Seasonal totals are also given for the official heating season that extends from 1 July to 30 June and the official cooling season from 1 January to 31 December. Comparisons are also provided for these monthly and seasonal values with the corresponding 30-year average values that currently cover the 1981-2010 interval.

Annual summaries also include the extremes in temperature, precipitation, and snow that have been observed at that current observing site. Since many of the weather stations have moved from city offices to airport locations, the noted extremes may not be the all-time extremes for that city.

Part 1: Modern Climate Science

Driving Question: *What is Earth's climate system and what are the empirical and dynamic definitions of climate?*

Educational Outcomes: To identify some of the many reasons for studying Earth's climate system. To learn more about the workings of Earth's climate system and become more aware of the significance of climate, climate variability, and climate change for our well being wherever we live.

An Earth System Approach:

A view of the Earth system as seen from space is presented in **Figure 1**. The image shown is a visible light full-disk view from a U.S. weather satellite positioned about 36,000 km (22,300 mi) above the equator in South America at 75 degrees W longitude. The satellite remains at that location relative to Earth's surface because it makes a full revolution around the planet as Earth makes one rotation in the same direction. Being geostationary, the satellite provides a continuous view of the same underlying surface. Successive images from this vantage point provide animations of whatever can be seen moving across Earth's surface, including the boundaries, called terminators, which separate the illuminated day side and dark night side of our planet.

Examine Figure 1, noting the outlines of land masses. The center of the disk is the point on Earth directly under the satellite from which this image was acquired. Place a dot on the image to represent this sub-satellite point and draw a horizontal line, representing the equator, through the point and extended to the edges of the Earth disk. Approximately one-third of Earth's surface can be seen from the satellite.

1. Figure 1 is a view of the Earth system with the edge of the disk marking the boundary between Earth and the rest of the universe. It is evident from the sharpness of the edge between Earth and space that the atmosphere must be a thin layer compared to Earth's diameter. Since the full disk appears sunlit in this visible image, the local time at the sub-solar point must be near **[(*noon*) (*sunset*)(*sunrise*)]**.

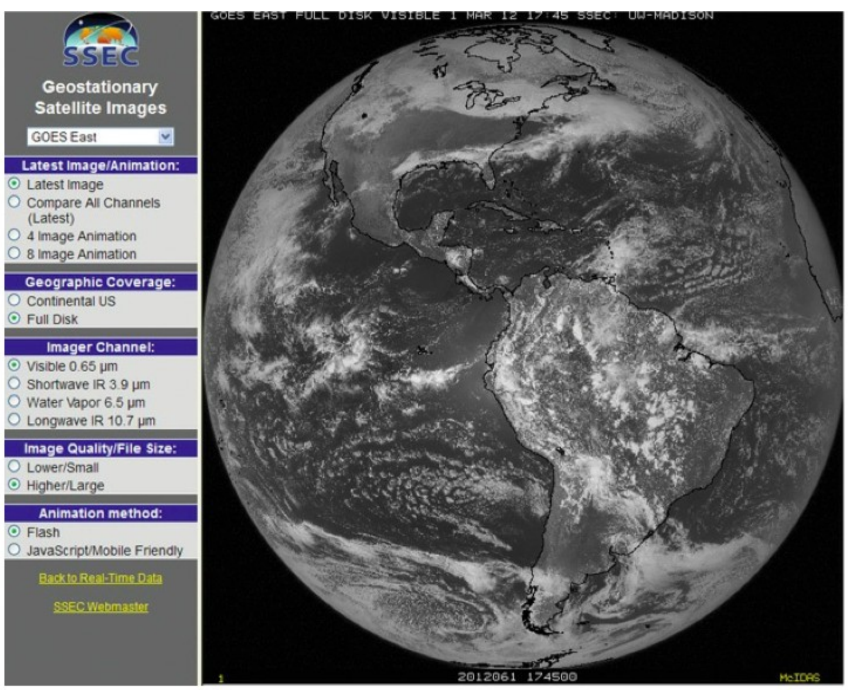

Figure 1.
Visible image of Earth from NOAA GOES East satellite at 1745 UTC on 1 March 2012. The time was 12:45 pm EST, 11:45 am CST, 10:45 am MST, 9:45 am PST.

2. Compare land and ocean surfaces in this view. As would be seen from other vantage points in space as well, Earth's surface is **[(*more*)(*less*)]** water than land.

Figure 1 is a static view of Earth's climate system. For a view of it in motion, go to:

http://www.ssec.wisc.edu/data/geo/index.php?satellite=east&channel=vis&coverage=fd&file=jpg&imgoranim=8&anim_method=flash, or *http://www.ssec.wisc.edu/data/geo/index.php?satellite=east&channel=vis&coverage=fd&file=jpg&imgoranim=8&anim_method=jsani*

Short Cuts! Please note that all web addresses appearing in these investigations are available on the course RealTime Climate Portal by clicking on "Investigations Manual Web Addresses". Under the particular Investigation heading, click on the link shown.

You are viewing the University of Wisconsin Space Science and Engineering Center (SSEC) website from which Figure 1 was acquired. The animation that appears is composed of eight recent full-disk images from the GOES East satellite, most acquired at three-hour intervals with the latest being only a few hours old. View the animation that essentially covers one day as it repeats through several cycles. To look at individual images or to slow down the animation, use the control bar above the image. First, click on "stop". Then click successively on the step-forward (>) button while noting the progression of day and night on Earth's surface as the rotating planet intercepts the radiant energy from the distant Sun.

3. Half of Earth's surface is in sunlight and half in darkness. The sunlit portion in the image shows the part of Earth in the satellite's field of view that is receiving energy from outside the Earth system. The animation shows that the solar energy coming into the Earth system at any location is **[(*continuous, constantly illuminating the surface*) (*received in pulses, alternating between periods of sunlight and no sunlight*)]**.

4. The time of each image is printed across the top, after the date. Stop the animation at the 1745 UTC image, the same time of day as the Figure 1 image. Compare it with Figure 1. The major observable differences in the two images arise from the Earth system's **[(*land surfaces*)(*ocean surfaces*)(*atmosphere*)]**.

Because these images are visible light images (essentially conventional black and white photographs), features are distinguished by the variation and quality of reflected sunlight. Generally, the brighter (whiter) the feature, the greater the reflection of solar radiation directly back to space. Conversely, darker areas indicate greater absorption of the incoming solar energy.

5. Generally, the image shows that **[(*land surfaces*)(*water surfaces*)(*cloud tops*)]** are places where the greatest amount of incoming solar energy is absorbed into the Earth system.

On the SSEC Geostationary Satellite Images browser menu to the left, click on the Imager Channel "Longwave IR 10.7 μm" button. Here you are viewing images of "heat" radiation emitted by the Earth system out to space. In these IR images, the darker areas represent those places where outgoing heat radiation to space is greater, and lighter areas denote less outgoing heat radiation. Essentially, these are images of temperature. The darker the shading, the higher the temperature of the surface from which the radiation is being emitted and the greater the rate at which heat energy is being lost to space.

6. Comparison of the IR animation with the visible light animation shows that the Earth system emits IR to space **[(*continuously*)(*only on the night side of Earth*)]**.

7. Step through the IR animation for several cycles and look for broad, essentially cloud-free places where shading changes most, that is, they alternate between dark shading (meaning they reach relatively high temperatures) and light shading (meaning cooler temperatures) over the period of a day. These locations are **[(*land*)(*water*)]** surfaces.

8. Stop the IR animation on the image with places shaded darkest and note the time of the image. Switch to the visible imagery by going to the browser menu and stopping the animation at the same time. The comparison shows that the highest surface temperatures occur within a few hours of local **[(*midnight*)(*sunrise*)(*mid-day*)]**.

In summary, you have been introduced to the Earth system, the receipt of sunlight into the Earth system from space (incoming energy), and the emission of IR (heat) from Earth to space (outgoing energy).

That part of our planet (including the atmosphere, ocean, land, biosphere and cryosphere) subjected to solar energy flowing into, through, and out of the Earth system, is ***Earth's climate system.***

Weather, Climate and Climate Change:
Fundamental to an understanding of weather, climate and climate change, is the recognition that the Earth's climate system is a complex system of energy flow, as alluded to by animations of visible and IR full-disk views of Earth. The observable impacts of the energy flows (and the associated mass flows) are embodied in the descriptions of weather and climate.

Weather is concerned with the state of (i.e., conditions in) the atmosphere and at Earth's surface at particular places and times. Weather, fair or stormy, is not arbitrary or capricious. Both its persistence and its variability are determined by energy and mass flows through the Earth system.

Climate is commonly thought of as a synthesis of actual weather conditions at the same locality over some specified period of time, as well as descriptions of weather variability and extremes over the entire period of record at that location. Climate so defined can be called ***empirical,*** i.e., dependent on evidence or consequences that are observable by the senses. It is empirical as it is based on the descriptions of weather observations in terms of the statistical averages and variability of quantities such as temperature, precipitation and wind over periods of several decades (typically the three most recent decades).

Climate can also be specified from a ***dynamic*** perspective of the Earth environment as a system. The definition of Earth's climate system must encompass the hydrosphere including the ocean, the land and its features, the biosphere, and the cryosphere including land ice and snow cover, which increasingly interact with the atmosphere as the time period considered increases. While the transitory character of weather results from it being primarily an atmospheric phenomenon, **climate exhibits persistence arising from it being essentially an Earth system phenomenon.**

From the dynamic perspective, climate is ultimately the story of solar energy intercepted by Earth being absorbed, scattered, reflected, stored, transformed, put to work, and eventually emitted back to space as infrared radiation. As energy flows through the Earth system, it determines and bounds the broad array of conditions that blend into a slowly varying persistent state over time at any particular location within the system.

Whereas the empirical approach allows us to construct descriptions of climate, the dynamic approach enables us to seek explanations for climate. Each has its powerful applications. In combination, the two approaches enable us to explain, model and predict climate and climate change. In this course we will treat climate from the two complementary perspectives.

9. In its definition of **climate**, the AMS ***Glossary of Meteorology, 2nd. ed., 2000,*** states that climate "*… is typically characterized in terms of suitable averages of the climate system over periods of a month or more, taking into consideration the variability in time of these average quantities.*" This definition is derived from a(n) **[(*empirical*)(*dynamic*)]** perspective.

10. The ***AMS Glossary***'s definition continues: "*... the concept of climate has broadened and evolved in recent decades in response to the increased understanding of the underlying processes that determine climate and its variability*." This expanded definition of climate is based on a(n) **[(*dynamic*)(*empirical*)]** perspective.

11. Local climatic data, including records of observed temperature, precipitation, humidity, and wind, are examples of **[(*dynamically*)(*empirically*)]** derived information.
12. The determination of actual **climate change**, also from the ***AMS Glossary***, ("*any systematic change in the long-term statistics of climate elements sustained over several decades or longer*") is based primarily on evidence provided from a(n) **[(*dynamic*)(*empirical*)]** perspective.

13. Also from the ***AMS Glossary***, "*Climate change may be due to natural external forcings, such as changes in solar emission or slow changes in Earth's orbital elements; natural internal processes of the climate system; or anthropogenic (human caused) forcing*." This is a statement derived from a(n) **[(*dynamic*)(*empirical*)]** perspective.

14. Scientific predictions of such an altered state of the climate (i.e., climate change) must be based on treating Earth's climate system from a(n) **[(*dynamic*)(*empirical*)]** perspective.

***Earth's Climate System (ECS)* Paradigm:**

Utilizing a planetary-scale Earth system perspective, this course explores Earth's climate system. In pursuing this approach, understanding is guided and unified by a special paradigm:

AMS Climate Paradigm

The climate system determines Earth's climate as the result of mutual interactions among the atmosphere, hydrosphere, cryosphere, geosphere, and biosphere and responses to external influences from space. As the composite of prevailing weather patterns, climate's complete description includes both the average state of the atmosphere and its variations. Climate can be explained primarily in terms of the complex redistribution of heat energy and matter by Earth's coupled atmosphere/ocean system. It is governed by the interaction of many factors, *causing climate to differ from one place to another and to vary on time scales from seasons to millennia. The range of climate, including extremes, places limitations on living things and a region's habitability.*

Climate is inherently variable and now appears to be changing at rates unprecedented in recent Earth history. Human activities, especially those that alter the composition of the atmosphere or characteristics of Earth's surface, play an increasingly important role in the climate system. Rapid climate changes, natural or human-caused, heighten the vulnerabilities of societies and ecosystems, impacting biological systems, water resources, food production, energy demand, human health, and national security. These vulnerabilities are global to local in scale, and call for increased understanding and surveillance of the climate system and its sensitivity to imposed changes. Scientific research focusing on key climate processes, expanded monitoring, and improved modeling capabilities are increasing our ability to predict the future climate. Although incomplete, our current understanding of the climate system and the far-reaching risks associated with climate change call for the immediate preparation and implementation of strategies for sustainable development and long-term stewardship of Earth.

15. It is implied in the ***AMS Climate Paradigm*** that components of Earth's climate system (e.g., atmosphere, hydrosphere, cryosphere, geosphere, and biosphere) interact in a(n) **[(*random*) (*orderly*)]** way as described by natural laws.
16. This interaction of Earth system components through natural laws would imply a(n) **[(*dynamic*) (*empirical*)]** perspective for climate studies.

17. The ocean as an Earth system component and player in atmosphere/ocean energy and mass distributions suggest it is a **[(*minor*)(*major*)]** part of biogeochemical cycles (e.g., water cycle, carbon cycle) operating in the Earth system.

18. According to the ***AMS Climate Paradigm***, our understanding of Earth's climate system is incomplete. Nonetheless, it states that the risks associated with climate change call for the development and implementation of **[(*sustainable development strategies*)(*long-term stewardship of our Earthly environment*)(*both of these*)]**.

Summary:

In this course we will investigate climate, climate variability, and climate change through complementary **empirical** and **dynamic** approaches guided by the ***AMS Climate Paradigm.***

Part 2: FOLLOW THE ENERGY! EARTH'S DYNAMIC CLIMATE SYSTEM

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 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 clear, cloud-free 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 H_2O and 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.

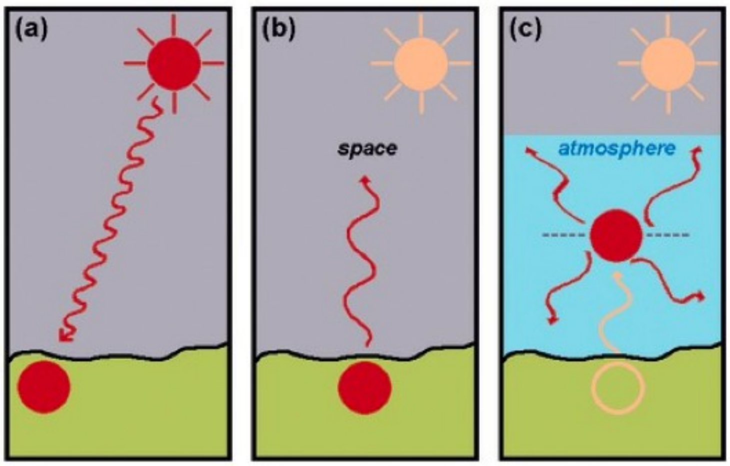

Figure 1.
(a) Sunlight heats the surface of the planet. (b) In absence of an atmosphere, the surface emits infrared radiation to space. (c) If there is an atmosphere, greenhouse gases absorb infrared radiation emitted from the planet's surface and then radiate the energy in all directions, with half 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 RealTime Climate Portal and in the **"Extras"** section, click on AMS Conceptual Energy Model. Then click on *Run the AMS CEM* found in the Climate Science Links.

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.

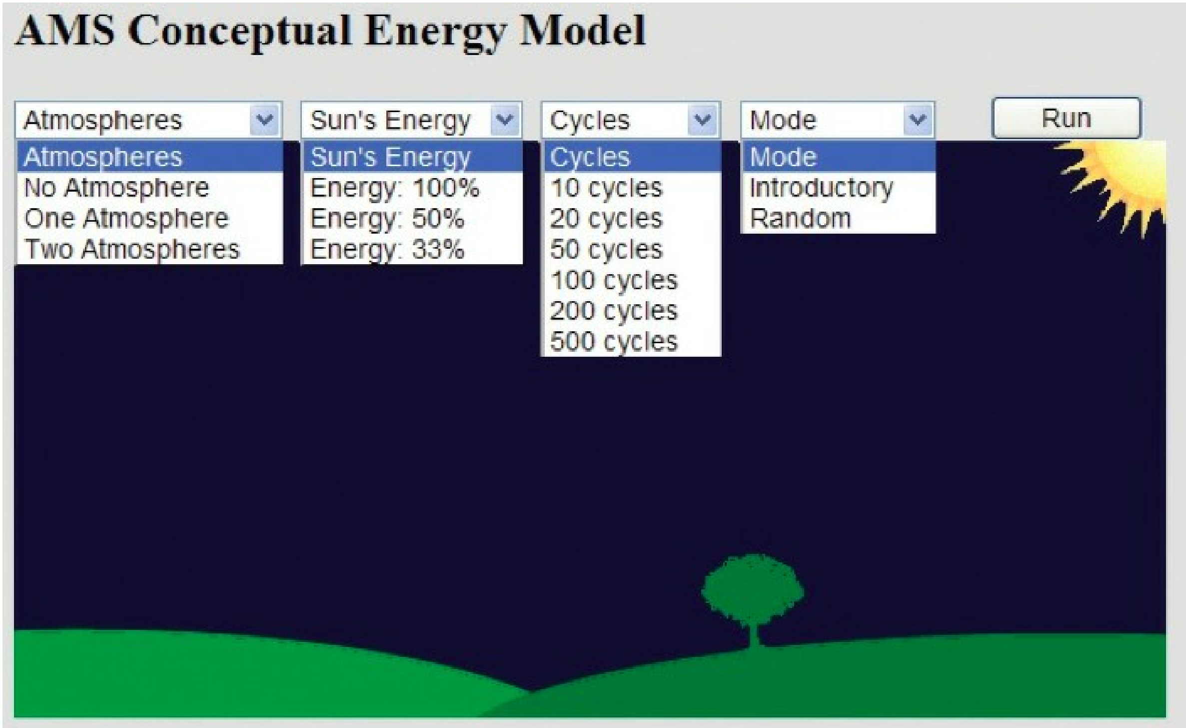

Figure 2.
Landscape view of AMS CEM showing possible choices or settings to conduct model runs.

Become acquainted with the AMS CEM. Start by selecting "One Atmosphere" under **Atmospheres** and "Energy: 100%" under **Sun's Energy** (denoting the arrival of a fresh unit of energy from the Sun during each cycle of play). 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 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:

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_2, H_2O), the energy emitted from the gas molecule can be 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 the cycle following its arrival from the Sun, the second energy unit 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 it is extremely unlikely any 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 in 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 Introductory-mode 200-cycle run ranged between **[(*0*)(*1*)(*3*)(*5*)]** and 8.

12. Even with the model settings being the same throughout the 200-cyce 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 **[(*less than*)(*equal to*)(*more than*)]** the rate of incoming energy from space.

Keeping other settings the same, switch to the Random mode. Try several runs of the model to see differences and similarities in 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 can be referred to as examples of ***natural variability*** as 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.

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. We will then be observing evidence of ***climate change***.

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 carbondioxide 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.

13. 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 **[(*almost all*)(*about half*)(*few*)]** of the processes and interactions between climate system components (e.g., precipitation-evaporation, land-atmosphere) involve bi-directional (upward/downward) flows.

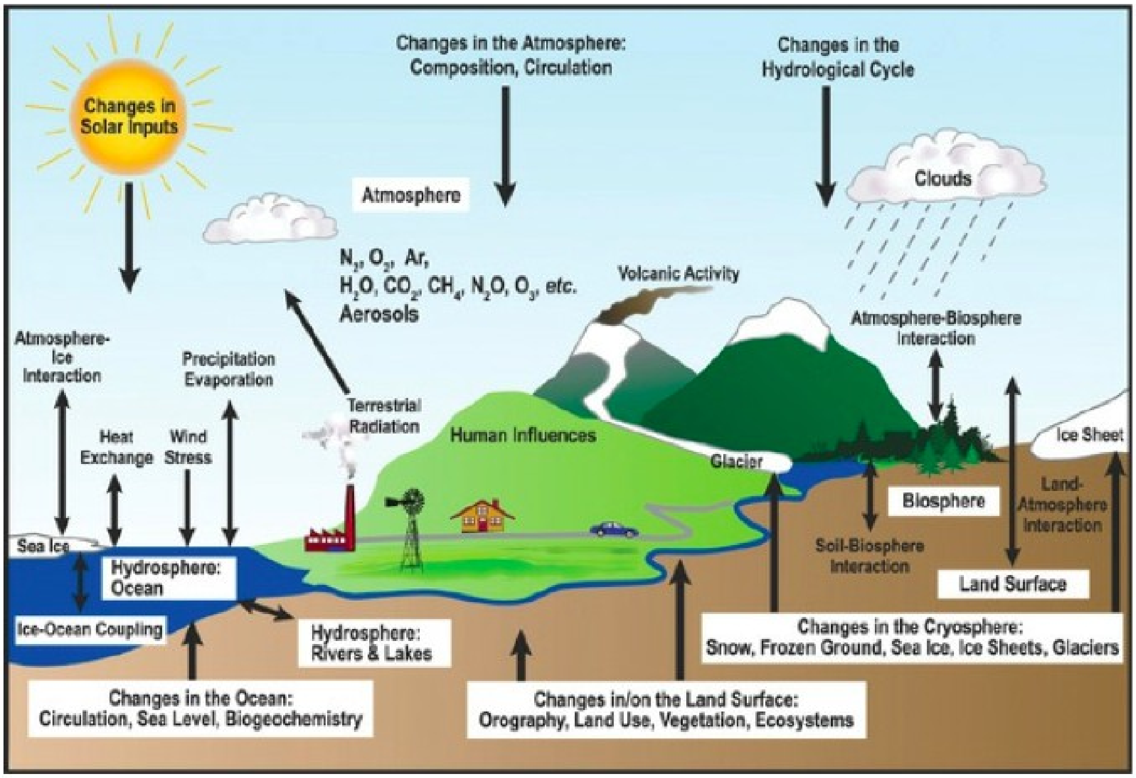

Figure 3.
Schematic view of the components of Earth's climate system, their processes and interactions. [IPCC AR4 WG1 faq-1-2-fig-1]

14. Six of the interactions depicted in Figure 2 are specifically labeled "*Changes in …*" "Changes" imply forcing that results in climate change. While the human impact that most impacts global climate is change in the atmosphere (composition), the human impact most observably altering the local or regional climate is the one concerning the **[(*ocean*)(*hydrological cycle*)(*cryosphere*) (*land surface*)]**.

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 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/*.