Climate Science

SOLAR ENERGY AND EARTH’S CLIMATE SYSTEM / ATMOSPHERIC CO2, INFRARED RADIATION, AND CLIMATE CHANGE

TRACKING SUN PATH AND SUNRISE/SUNSET TIMES

Background:

Have you ever needed to know where the sun appears in the sky on a particular day or when the sun would set in your town? Tracking the sun's path through the sky on a given day may be important if you would desire to install a solar energy collector. Knowledge of the time of sunset or sunrise may be needed for planning purposes, for legal matters or for scientific investigations.

Tracking the Sun across the sky

We know that during the summer, the sun passes high in the sky, while in winter the sun takes a low path across the sky. But can we accurately track the sun's path across our sky? One can calculate the path of the apparent sun across the sky for any place using well known angular relationships that take into account the latitude of the observer (how far one is from the equator in angular measure) and the day of the year (which essentially describes the seasonal course of the tilt of the earth's spin axis with respect to the sun). The *Climate Studies* text shows the paths of the sun on the first days of the astronomical seasons in the midlatitudes where most of us live. We are now in the part of the year when the combination of the inclination of the Earth's axis to its orbital plane and the movement of our planet along its orbital path are tilting the Northern Hemisphere more and more toward the Sun. Our daylight periods are getting longer and the noon sun is ever higher in the sky.

The U.S. Naval Observatory has an interactive online service that allows you to track the sun for your hometown or any other location in the United States and the world in a sun altitude/azimuth table. This table provides the position of the sun in the local sky at 10-minute intervals during any day, from approximately one hour before local sunrise to roughly one hour after sunset. The position of the sun is determined by two angles: the altitude angle of the sun and its azimuth angle. The altitude angle is the angle of that the sun is above the local theoretical horizon, with an altitude angle of zero degrees referring to the sun on the horizon, while a 90 degree altitude angle would be if the sun were directly above you (at the local zenith). A negative altitude angle means that the sun is below the horizon, such as before sunrise. The azimuth angle is the angle measured in a clockwise direction from true north (or to the east), commencing at zero or 360 degrees and passing through 90 degrees (due east).

Local Sunrise/sunset times

The local times of sunrise and sunset for each day of the year are provided by many almanacs and appear in the media, such as in the newspapers or on television. These times are defined as the instant when the top of the solar disk is just at the local level horizon. Like the positions of the sun at various times during the day, the sunrise/sunset times can be calculated using well-known trigonometric relationships for any latitude and the day of the year. The U.S. Naval Observatory has prepared sunrise-sunset tables for over 200 locations throughout the country. Inspecting these tabulations reveals several interesting features. An on-line, interactive service is available that allows you to determine the times of sunrise or sunset for individual days or the entire year at most cities in the United States.

Daily Changes in sunrise/sunset

At this time of the year -- the week before the autumnal equinox-- we are often struck by the rapid change in sunset (and sunrise) time from day to day, translating into a decrease in daylight. These changes are also related to latitude. On one extreme, northernmost Barrow, AK loses approximately 9 minutes of daylight per day during mid September, while at the same time, one of southern-most cities, Honolulu, HI loses 1 minute of possible sunshine per day. However, near the solstices the times of sunrise and sunset change very slowly on a daily basis; in fact, the word solstice is derived from the Greek word meaning "stand still".

The orientation of the earth's spin axis with respect to the sun is responsible for this seasonal variation in the timing of sunrise and sunset. At the equinoxes the earth's axis has no apparent inclination to the sun meaning that rapid day-to- day changes in the apparent position of the sun are greatest, while at the solstices, the inclination is greatest and daily changes of the apparent sun are smallest.

Effects of atmospheric refraction

If you have a chance, you should look at the published local times of sunrise and sunset for a close city on the day of the autumnal equinox (Sunday, 22 September 2013). If you had a chance, did you look at the published local times of sunrise and sunset for a close city on the autumnal equinox during this week? Otherwise, check on the day of the vernal equinox next spring. If you determined the length of sunlight from the time elapsed between local sunrise and sunset, you would find that on the equinox you would experience slightly more than 12 hours of possible sunlight; in mid latitudes this additional time is on the order of 8 minutes.

The primary reason for these extra minutes is the result of the slight bending of the sun's rays as they penetrate through an increasingly more dense planetary atmosphere. This phenomenon is called "atmospheric refraction". You have probably observed this refraction phenomenon when the pencil that is partially submerged in a glass of water appears crooked. In the morning, this ray bending causes the sun to appear above the horizon although the sun is actually below the horizon by approximately one half of a degree of arc. A second factor contributing to the extended time lies in the fact that the sun is not a point, but has a radius of one quarter of a degree of arc. At sunrise, the top rim of the apparent sun has been above the local horizon 4 minutes before the center of the actual sun would have reached the horizon without an atmosphere. Likewise at sunset, the sun appears to remain above the horizon for an additional 4 minutes, when in fact the solar disc has already disappeared.

Times of sunrise and sunset near the solstices

In December, you will notice that the earliest sunsets at most locales occurred during the first or second week of December, while the latest sunrise occurs during the first two weeks of January. (The exact dates depend upon your latitude.) So as not to worry about these apparent oddities, the shortest daylight period of the year does indeed fall on the winter solstice, on or about 21 December.

This apparent asymmetry in the timing of sunrise/sunset occurs because the sun is not as good a timekeeper as most of our clocks. Since the earth revolves around the sun in an elliptical orbit and the spin axis is tilted from the orbital plane, the sun appears to move across the local sky at somewhat variable speeds throughout the year, rather than at a precise 15 degrees per hour. While the differences on any one day are small, over several weeks these slight departures accumulate between true sun time and mean sun time. These accumulated discrepancies are very apparent at certain times of the year, such as the sun running 15 minutes "fast" in early November but by early February, the sun appears to have slowed to the point where it runs 12 minutes "slow". A change from the sun running fast to running slow occurs during December, the result of two events that occur relatively close together: winter solstice in late December and perihelion passage in early January.

This effect works in reverse in summer, when the earliest sunrises occur in early June while the latest sunsets can occur during the first week of July. However, the longest sunlight of the year does indeed culminate on about 21 June. At this time, the solar geometry associated with both aphelion passage and summer solstice contribute to an apparent slowing of the "solar clock".

Part 1: SOLAR ENERGY AND EARTH’S CLIMATE SYSTEM

Driving Question: *How does solar energy received by the Earth vary during the year at different latitudes?*

Educational Outcomes: To describe how the amount of solar radiation intercepted by Earth varies at different latitudes over the period of a year. To learn how changes in the Sun’s path through local skies impact the amount of incident solar radiation. To make comparisons of how much solar radiation is received at tropical, midlatitude, and polar locations at different times of the year. To estimate the impact of the atmosphere on incoming solar radiation by comparing the amount received at Earth’s surface with that striking the top of the atmosphere.

Objectives: Climate can be thought of as 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. The solar energy entering the Earth system is the ultimate boundary condition of climate as the Sun is the source of energy that heats Earth’s climate system.

After completing this investigation, you should be able to:

- Describe the variation of solar radiation received at the top of the atmosphere at equatorial, midlatitude, and polar locations over the period of a year.
- Compare the amounts of solar radiation received at a midlatitude location at the top of the atmosphere and at Earth’s surface under clear-sky and average conditions during different times of the year.

Incoming Solar Radiation

Over the period of a year the amount of solar radiation received at Earth’s surface varies considerably at most latitudes. This variation is governed largely by the boundary condition arising from the changing paths of the Sun through the local sky, due to Earth rotating on an axis inclined to the plane of its annual orbit about the Sun. These planetary motions constantly change the part of Earth’s surface bathed by the Sun’s rays. Every latitude on the globe has its own annual pattern of incident sunlight. These patterns are governed by the shifting path of the Sun through the local sky and the lengths of daily periods of daylight. These variations are primarily responsible for the unequal distribution of absorbed solar energy from the equator to the poles that drives Earth's climate system.

Figure 1 displays the approximate paths of the Sun through the local sky at (A) the equator, (B) a middle latitude location in the Northern Hemisphere, and (C) the North Pole on the first days of summer, fall, winter, and spring. The paths are continuously changing through perpetual annual cycles. Among the variations by latitude, at the equator the periods of daylight are a constant half-day throughout the year, while at the pole there is one period of sunlight through the year that lasts continuously for six months.

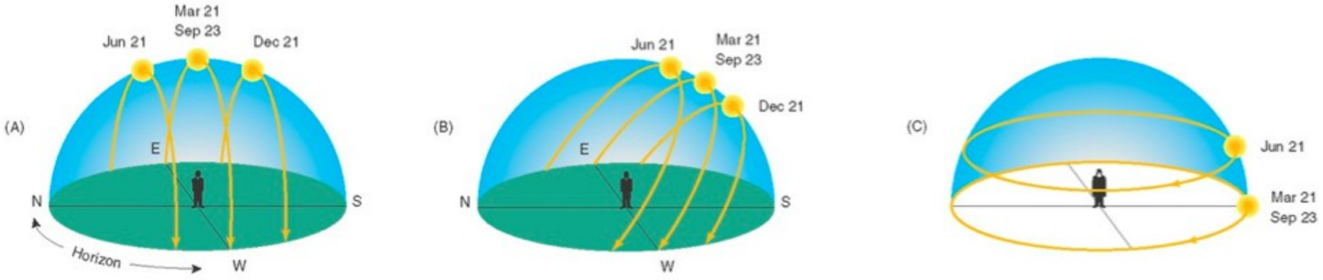

Figure 1.
Path of Sun through the sky on the solstices and equinoxes at (A) the equator, (B) a middle latitude location in the Northern Hemisphere, and (C) the North Pole.

At the top of the atmosphere when Earth is at its mean distance from the Sun, an average of about two calories of solar energy per minute strikes a square centimeter (1.4 kilowatts per square meter or 0.14 watt per square centimeter) of a flat surface oriented perpendicular to the Sun's rays. This average rate is called the ***solar constant***. The rates at which solar energy penetrating the atmosphere actually strikes Earth's surface are quite different and highly variable. At any instant, the only point at which the Sun's rays are perpendicular to Earth's surface is where the Sun is in the zenith. That sub-solar point races steadily around the planet once a day as it follows an annual path that spirals between 23.5 degrees North and 23.5 degrees South latitudes. Twice a year, on the vernal and autumnal equinoxes, the Sun is positioned directly above the equator. During the time between the vernal and the succeeding autumnal equinox the sub-solar point is located in the Northern Hemisphere, while from the autumnal to the following vernal equinox, the sub-solar point is positioned in the Southern Hemisphere. The solstices occur when the sub-solar point reaches its maximum latitude positions (23.5° N on the first day of the Northern Hemisphere's summer in late June and 23.5° S on the first day of our winter in late December).

The Earth, spinning on an axis inclined 23.5 degrees from a line perpendicular to the plane of its orbit, presents an ever changing face to the Sun. Wherever daylight occurs, the path of the Sun through the local sky changes from day to day. Except at the equator, or at high latitudes when there are days of continuous daylight or darkness, the daily length of daylight also changes. Clouds, air molecules, and aerosols (tiny particles suspended in air) reduce the amount of solar radiation reaching Earth's surface. Some solar radiation is absorbed by atmospheric components and some is scattered or reflected back to space.

Because absorbed solar radiation is the fundamental driver of Earth's climate system, the purpose of this activity is to investigate the variability of solar radiation received at the top of the atmosphere and at Earth's surface at different latitudes over the period of a year.

The great variation in the solar radiation received at different latitudes throughout a year is primarily responsible for the temperature contrasts that result in the fluid parts of the Earth system (atmosphere and ocean) transporting huge quantities of heat energy from lower to higher latitudes. These energy flows accompany the weather patterns and temperature variations that characterize the seasons.

Effects of Latitude on Incoming Solar Radiation

What impacts do latitude and the atmosphere have on incoming solar radiation? NASA provides monthly averaged top-of-atmosphere insolation values as well as those incident on a horizontal surface at Earth's surface for any global location (*http://eosweb.larc.nasa.gov/cgi-bin/sse/sizer.cgi? email=na*). The term ***insolation*** is short for ***in***coming ***sol***ar radi***ation***. The top-of-atmosphere values would be the amount received at Earth's surface if there were no atmosphere. The NASA data report incident solar radiation in units of kilowatt hours per square meter per day ($kWh/m^2/day$). [For conversion purposes, 1 cal/cm^2 = 0.01 kWh/m^2.]

Figure 1(A) shows daily paths of the Sun at an equatorial location on the solstices and equinoxes. **Figure 2** displays a red curve that depicts the daily average solar radiation striking a horizontal surface at the top of the atmosphere over a location on the equator (0° Latitude). Data of average daily values for each month are plotted at mid-month. Draw and label straight vertical lines on Figure 2 on the approximate dates of the Northern Hemisphere's vernal equinox (21 March), summer solstice (21 June), autumnal equinox (23 September), and winter solstice (21 December).

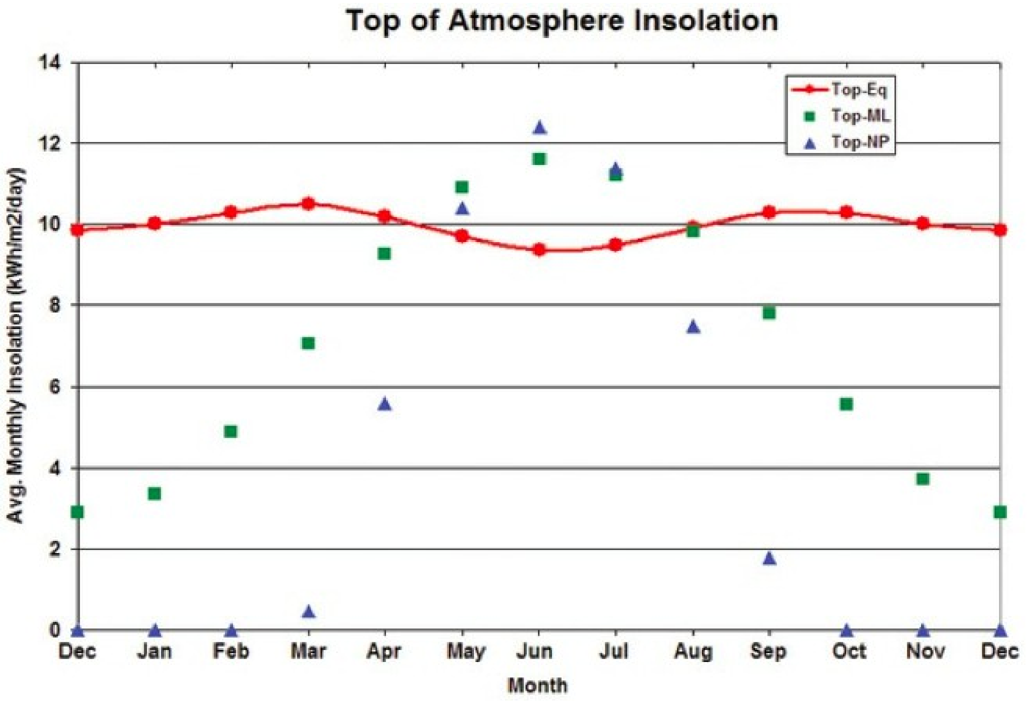

Figure 2.

NASA-generated average monthly top-of-atmosphere solar radiation (in $kWh/m^2/day$) at equator (Eq), midlatitude (ML), and North Pole (NP).

1. Note the two maxima and two minima portions of the Figure 2 equatorial insolation curve over the period of a year. Figure 2 shows that the minimum portions of average daily solar radiation values at the top of the atmosphere over the period of a year occur during the months of **[(*March and September/October*)(*June and December*)]**. These occur when the sub-solar point is at its highest latitudes for the year, as seen in Figure 1(A).

2. The equatorial top-of-atmosphere curve in Figure 2 shows that the two insolation maxima occur near the times of the **[(*solstices*)(*equinoxes*)]**. Because places on the equator experience essentially the same period of daylight (approximately 12 hours) every day of the year, the changes in the top-of-atmosphere radiation values over the year must be due primarily to changes in the path of the Sun through the local sky (that is, changes in the maximum daily altitude of the Sun). Note that the top-of-atmosphere insolation values do not vary greatly over the year at the equator, with the minimum insolation value being about 90% of the maximum insolation value.

3. **Figure 1(C)** describes Sun's path through the local sky at the North Pole (90°N) on the summer solstice and the equinoxes. It shows that on these days, the Sun is on or above the horizon for **[(*0*) (*12*)(*24*)]** hours. It can be inferred from the drawing that the Sun is below the local horizon continuously from the fall equinox to the next spring equinox (assuming no atmospheric effects).

4. Plotted on Figure 2 are data points ( ) of monthly average daily top-of-atmosphere insolation at the North Pole (90° N). Assuming top-of-atmosphere insolation is zero on the equinoxes, connect the adjacent values by drawing a smoothed curve (with a blue pencil if available). The curve shows the North Pole receives essentially no incoming sunlight for **[(*0*)(*3*)(*6*)(*9*)(*12*)]** months a year. (The insolation pattern at the South Pole is similar except six months out of phase with that at the North Pole.)

5. Plotted on Figure 2 are data points ( ) of monthly average daily top-of-atmosphere insolation at 45 degrees North Latitude (45° N). Connect the adjacent values by drawing a smoothed curve (with a green pencil if available). The midlatitude curve makes it evident that the maximum insolation occurs on the summer solstice and minimum insolation occurs on the winter solstice. It can be determined from Figure 2 that on an average day in December the midlatitude location receives about **[(*25%*)(*50%*)(*75%*)(*100%*)]** of the top-of-atmosphere insolation it receives on an average June day.

6. The midlatitude curve is characterized by having one maximum value and one minimum value per year. Comparison of the curves now appearing on Figure 2 shows that the midlatitude location **[(*always*)(*sometimes*)(*never*)]** receives top-of-atmosphere insolation that is greater than what is received at the equator.

7. **Figure 1(B)** depicts Sun's paths through the midlatitude local sky on the solstices and equinoxes. The solstice paths demonstrate that changes in **[(*Sun's maximum altitude*)(*length of Sun's path*) (*both of these*)]** contribute to the midlatitude's annual range of daily insolation.

8. Comparisons of the three top-of-atmosphere curves drawn in Figure 2 demonstrate why latitude is considered as a fundamental control of climate. The insolation values over the period of a year

vary the most at the **[(*equatorial*)(*midlatitude*)(*polar*)]** location.

9. The **[(*equatorial*)(*midlatitude*)(*polar*)]** location experiences the least change in insolation, over the period of a year.

10. The three top-of-atmosphere insolation curves in Figure 2 indicate that during the year, the most intense daily insolation occurs at the **[(*equatorial*)(*midlatitude*)(*polar*)]** location.

Impacts of the Atmosphere on Incoming Solar Radiation

The rate at which solar energy is received at the top of the atmosphere is the fundamental boundary condition of Earth's climate system. **Figure 3** is presented to demonstrate the impact of the atmosphere on the sunlight entering the Earth system at a 45°N location (Salem, Oregon). The red curve drawn on the figure represents the same top-of-atmosphere insolation data for 45° N as seen in Figure 2.

11. The blue data points (   ) plotted on Figure 3 are calculated average monthly values of daily insolation received at Earth's surface at a 45° N location that would be observed under clear-sky conditions (no clouds). Create the annual clear-sky insolation curve by drawing a smooth curve through the data points (using a blue pencil if available). The figure shows that during the month of May, 10.9 kWh/m^2 of energy was received at the top of the atmosphere. The figure also shows that under continuous clear-sky conditions, it would receive about **[(*4.1*)(*6.1*)(*8.1*)]** kWh/m^2 on an average May day.

12. The May data shows that for that month about **[(*26%*)(*41%*)(*76%*)]** of the solar energy striking the top of the atmosphere is blocked by the clear atmosphere. This attenuation (loss) is due to solar radiation being absorbed by atmospheric gas molecules (H_2O and O_3) and particulates (dust) and by backscattering to space. Evaluation of the Figure 3 data for all 12 months produce about the same result. Global energy budget studies place the worldwide average for clear-air absorption and backscatter at about the same (actually, about 2% less).

13. The green data points ( ) plotted on Figure 3 are calculated average monthly values of daily insolation received at Earth's surface at a 45° N location that would be observed under average conditions (including clouds). Create the annual average surface insolation curve by drawing a smooth curve through the data points (using a green pencil if available). According to Figure 3, the May value for solar energy actually arriving at Earth's surface is **[(*4.1*)(*5.1*)(*8.1*)]** kWh/m^2 for an average day.

14. Compared with the May top-of-atmosphere value, it shows that the actual atmosphere (including clouds) blocks about **[(*37%*)(*53%*)(*76%*)** of the solar energy entering Earth's atmosphere at Salem, OR.

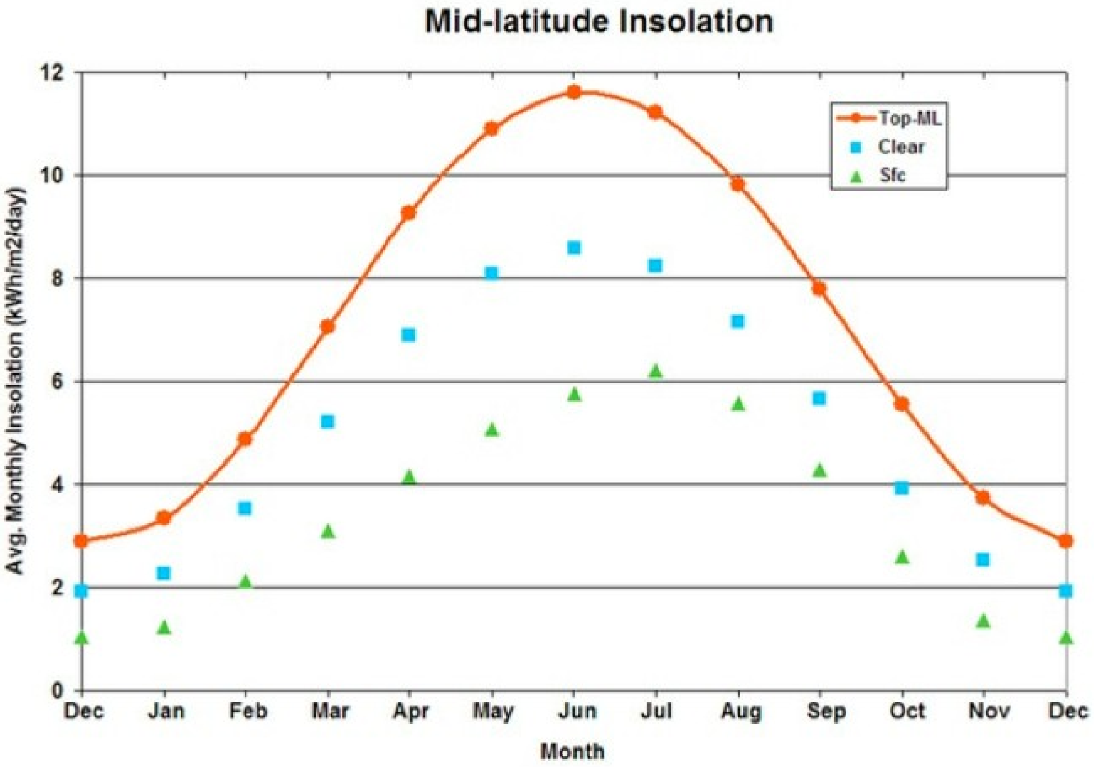

Figure 3.
NASA-generated daily averaged top-of-atmosphere, clear-sky and surface incident solar radiation data at Salem, OR, 45° N (in kWh/m^2/day).

Global energy budget studies place the worldwide average for actual atmospheric absorption and backscatter conditions (including clouds) at near, but slightly less than, the Salem, OR, May value as reported in Figure 3. Figure 3 shows that the differences between Salem's May top-of-atmosphere and clear-sky values (2.8 kWh/m^2/day) and the difference between clear-sky and actual surface insolation values (3.0 kWh/m^2/day) are nearly equal. This infers that clear air and cloudiness are both major factors in determining how much of the solar radiation arriving at the top of Earth's atmosphere is attenuated before reaching the surface.

15. Actual surface insolation data reported in Figure 3 shows that monthly average values at Salem, OR range from 1.1 kWh/m^2/day in December to **[(*4.1*)(*5.1*)(*6.2*)]** kWh/m^2/day in July.

16. The actual surface insolation curve in Figure 3 demonstrates the wide swing in the amount of solar radiation arriving at Earth's surface at a midlatitude location over the period of a year. According to the data in the previous item, Earth's surface at Salem receives on an average July day about **[(*2.1*)(*4.1*)(*5.6*)]** times as much solar energy as on an average December day.

Summary: The story of climate starts with Earth's interception of solar radiation. The amount of sunlight intercepted varies considerably by latitude and time of year. The amount that reaches Earth's surface is determined by astronomical factors (e.g., solar constant, spherical Earth, rotation) and attenuation by atmospheric effects (e.g., cloudiness, absorption, scattering). Incident solar radiation at a particular location has climate implications resulting from the magnitude, path of the Sun through the daytime sky, and duration of daylight.

The solar energy entering the Earth system is the ultimate boundary condition of climate as the Sun is essentially the only source of energy that heats the Earth system – particularly its land and water surfaces and atmosphere. The amount of solar radiation received at Earth's surface varies considerably at most latitudes over the period of a year, setting the stage for annual climate swings. Although solar energy is essential in fueling the climate system, the Sun's energy intercepted by Earth is only the beginning of the story of climate.

ATMOSPHERIC CO_2, INFRARED RADIATION, AND CLIMATE CHANGE

Driving Question: *How does increasing the amount of carbon dioxide (CO_2) in the atmosphere impact the absorption of infrared radiation (IR) and average global surface temperature?*

Educational Outcomes: To describe the greenhouse effect of absorption and emission of infrared radiation (IR) by carbon dioxide (CO_2). To summarize from experimental evidence the changes in the absorption of IR as concentrations of atmospheric CO_2 increase. To demonstrate the impact of changing atmospheric CO_2 concentration on average global surface temperature as determined by a global climate model.

Objectives: After completing this investigation, you should be able to:

- Explain the greenhouse effect of IR absorption and emission by atmospheric CO_2 that results in higher atmospheric temperatures.
- Describe the impact of increasing the proportion of carbon dioxide in the atmosphere on absorption of IR and on temperature.
- Based on the investigation of CO_2, list fundamental understandings of how it and other greenhouse gases contribute to climate change.

The Atmospheric Greenhouse Effect

This investigation focuses on CO_2 to explore fundamental scientific understandings common to all atmospheric greenhouse gases.

Energy arrives at Earth as solar radiation, most intensely in the visible light portion of the electromagnetic spectrum. About half of the incoming radiant energy is reflected back to space (31%) or absorbed in the atmosphere (20%) while the other half is absorbed by Earth's surface. The heated surface then radiates IR upward, which is largely absorbed by atmospheric gas molecules including H_2O, CO_2, CH_4, and N_2O. These gas molecules emit the absorbed energy in all directions, half with an upward component and half in a downward direction, as demonstrated by the AMS CEM. By returning half of what they absorb back towards Earth's surface, these gases entrap heat within Earth's climate system. This is the ***greenhouse effect***.

Energy leaves the Earth system through the upper reaches of the atmosphere as IR. An increase in the concentration of greenhouse gases leads to temperatures in the troposphere (lower atmosphere) and at the surface increasing until a new planetary balance is achieved between solar radiation absorbed by the Earth system and IR exiting the Earth system.

1. As described above (and also a fundamental concept embodied in the AMS CEM), atmospheric greenhouse gas molecules absorb IR rising from Earth's surface and subsequently radiate IR **[(*only downward*)(*randomly in all directions*)(*only upward*)]**.

2. Because of this radiation pattern, half of the IR emitted by the greenhouse gas molecules is directed earthward. The net effect is a trapping of heat energy in the Earth system and an increase in surface and tropospheric temperatures. If the proportion of greenhouse gases in the atmosphere increases but then steadies out to a constant value, the amount of IR escaping to space will adjust until a planetary balance exists between it and the amount of incoming solar radiation being absorbed by the Earth system. Under these conditions (and with a continuing steady supply of sunlight), global average surface and tropospheric temperatures will **[(*increase*) (*remain the same*) (*decrease*)]** over the long term.

3. An increase in the amount of a greenhouse gas in the atmosphere reduces the transmission of IR through the air at certain wavelengths. ***Transmittance*** is a measure of the percentage of electromagnetic radiation of a specified wavelength that passes through a substance, such as IR through the atmosphere. The less the transmittance, the greater the amount of IR that has been absorbed. This, in turn, causes a rise in global-scale tropospheric and surface temperatures. These temperature increases are associated with a(n) **[(*increase*)(*decrease*)]** in the transmittance of IR through the atmosphere.

Fundamentals of IR Absorption by Atmospheric Molecules

Atmospheric molecules are constantly vibrating, but they vibrate only in certain ways at certain frequencies depending on their unique compositions, masses and structures. These characteristics determine what wavelengths of electromagnetic radiation they will absorb and emit. The two most abundant atmospheric gases, nitrogen (N_2) and oxygen (O_2), exist as symmetric molecules which do not absorb or emit most radiant energy so that they are essentially invisible (or transparent) to the majority of both incoming sunlight and Earth's IR emissions. Their transmittance is essentially 100%. There are other gases, including CO_2, that are transparent to visible light but readily absorb and emit wavelengths of radiant energy in the IR portion of the electromagnetic spectrum. This is because they have vibrational modes that absorb energy in the IR wavelengths which Earth's surface radiates towards space. Increasing concentrations of these gases reduce the transmittance of IR at these radiation-sensitive wavelengths and, at high enough concentrations, can reduce transmittance to 0%. Their sensitivity at those IR wavelengths at which Earth's surface radiation is most intense sets the stage for the greenhouse effect.

To see the impact of CO_2 on the transmission of IR, go to:

http://chemistry.beloit.edu/Warming/pages/infrared.html. Click on the graph to the upper right. The graph that appears shows data acquired with an IR spectrometer. A spectrometer is an instrument used to measure intensities of radiation over a specific portion of the electromagnetic spectrum. Absorption spectroscopy is employed by chemists and other scientists to identify and study chemicals, including gases. In this example, the IR spectrum is investigated in terms of how much of a pulsed IR signal is transmitted through a 10-cm path length across a range of wavelengths when the CO_2 concentration in a cell is varied.

4. In the graph, information along the x-axis is in terms of *wave number*, the number of wavelengths per cm. The larger the wavenumber, the shorter the wavelength along the IR spectrum. As the wavenumber values decrease from left to right in the graph, wavelengths become **[(*shorter*)
(*longer*)]** from left to right.

5. In the graph, the vertical scale plots transmittance of IR at different wave numbers. Transmittance of 100% indicates total transparency, while transmittance of 0% indicates total absorption of the IR at that wavenumber. In the graph, at the lower right, is a window indicating the concentration of CO_2 in the infrared cell as a gas pressure in units of millimeters of mercury (mm Hg). The initial graph shows that when the CO_2 concentration is 0, the IR spectrometer indicates a transmittance of essentially **[(*0%*)(*50%*)(*100%*)]** across the range of IR wave numbers covered by the graph.

6. To investigate transmittance as the concentration of CO_2 is changed in the IR cell, click on the button in the control bar below the graph. Each additional click on the button will present an IR spectrum for a greater concentration of CO_2. The graph shows that adding CO_2 causes transmittance of the IR signal through to the cell to be reduced **[(*the same across all wave numbers*)(*selectively at different wave numbers*)]**.

7. At wavenumbers where there is a reduction in transmittance, it means there is an increase in the amount of IR absorbed. IR absorption speeds up molecular motions, which produces **[(*a decrease*) (*no change*)(*an increase*)]** in temperature in the cell. What has been observed in these laboratory measurements also happens in Earth's atmosphere. That is because any medium that absorbs IR is heated.

8. On the graph, step through increasing CO_2 concentrations while noting changes in transmittance at IR-sensitive wave numbers. A 0% transmittance first occurs at a wavenumber of approximately**[(*650*)(*2350*)(*3700*)]** per cm. This is near the middle of a band of IR wavelengths most intensely emitted by Earth's surface.

9. Once a particular wavenumber or band of wavenumbers reaches a condition in which its transmittance has dropped to 0%, it is absorbing its maximum of IR. This condition is called ***saturation***, and no more IR can be absorbed at the particular wavenumber or band of wavenumbers. Additional increases in CO_2 concentration in the IR spectrometer cell **[(*will*)
(*will not*)]** result in additional absorption of IR at the saturated wavenumber(s).

10. On the graph, increase the CO_2 concentration over several steps while observing transmittance at the wavenumber where the transmittance curve first dropped to 0%. As the CO_2 concentration continues to increase after initial saturation, the width of the saturated wavenumber band along the base of the graph **[(*decreases*)(*increases*)(*shows no change*)]**.

11. On the graph, examine the change in transmittance in the absorption band centering on the same wavenumber where the transmittance curve first dropped to 0% as the CO_2 increases from 0 to 804 mm Hg. It can be seen that as the CO_2 concentration increases, the width of the vertical band (bandwidth) of wave numbers showing decreasing transmittance **[(*broaden*)(*narrows*)]**, providing evidence of IR absorption. (Note also another intense absorption band near wavenumber 650).

The changes in these bandwidths partially explain why a greenhouse gas does not suddenly stop changing climate when it reaches concentrations that produce wavenumber saturation in the atmosphere. The boundaries of an absorption band are not abrupt. Though the core of an absorption band may be saturated, its edges are not. A wavenumber at which IR is absorbed is not immediately adjacent to a wavenumber that absorbs no IR. The IR-sensitivity of neighboring wavenumbers changes over a range of wavenumbers, grading gradually from maximum absorption to no absorption. Consequently, as CO_2 concentration increases, wavenumbers next to saturated wavenumbers absorb IR and the absorption bandwidth increases.

The increase of CO_2 concentration in an unsaturated environment (where transmittance values are high) has a substantially greater impact on IR absorption than at CO_2 concentrations at which some wavenumbers have become saturated (transmittance has dropped to 0% at those wavenumbers). The greatest impact of greenhouse gas molecules, including CO_2, on absorbing IR occurs at their lowest concentrations.

Laboratory-based absorption spectroscopy studies conclusively prove that CO_2 selectively absorbs IR. They also demonstrate that the efficiency of CO_2 in absorbing IR changes as the concentration of the gas varies; the greater the concentration, the lower the efficiency. Attendant with the absorption of IR is increasing molecular vibration and accompanying heating and temperature rise.

Impact of Increasing CO_2 Concentrations in the Atmosphere

The behavior of atmospheric CO_2 follows the same fundamental laws of physics and chemistry as does CO_2 studied in a laboratory setting. What is learned in the controlled laboratory environment makes it possible to conduct informed studies of the complex Earth-atmosphere system with its highly variable and complex flows of energy and mass.

The impact of increasing atmospheric CO_2 concentrations on the average global surface temperature can be explored with a climate model application from the University of Chicago based on the National Center for Atmospheric Research's Community Atmosphere Model (CAM) (*http://www.ccsm.ucar.edu/models/atm-cam*).

While you are invited to visit and manipulate the University of Chicago model yourself (*http://geoflop.uchicago.edu/forecast/docs/Projects/full_spectrum.html*), the data in **Table 1** were acquired from the model which produces equilibrium near-surface air temperature values when top-of-atmosphere radiation balance has been achieved. [For reference, the current CO_2 concentration is about 390 ppmv (ppmv = parts per million by volume). A model run with this value produces a 16.1 °C surface temperature.]

12. Table 1 data show that increasing the atmospheric CO_2 concentration results in a temperature increase. Comparison of the temperature change per 10 ppmv CO_2 increase between 0 and 80 ppmv shows that as the CO_2 concentration increases, the temperature change per 10 ppmv increment **[(*increases*)(*decreases*)(*remains the same*)]**.

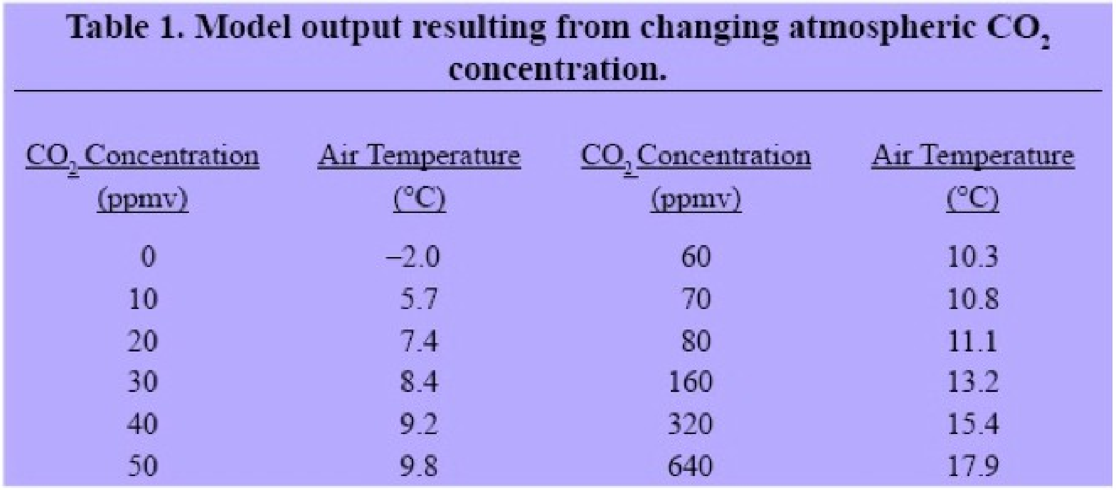

Table 1. Model output resulting from changing atmospheric CO_2 concentration.

CO_2 Concentration (ppmv)	Air Temperature (°C)	CO_2 Concentration (ppmv)	Air Temperature (°C)
0	–2.0	60	10.3
10	5.7	70	10.8
20	7.4	80	11.1
30	8.4	160	13.2
40	9.2	320	15.4
50	9.8	640	17.9

13. To determine the impact of doubling the proportion of CO_2 in the atmosphere, compare temperature changes calculated by the model. Note in Table 1 that when the CO_2 concentration doubles from 80 ppmv to 160 ppmv, the near-surface air temperature changes from 11.1 °C to 13.2 °C, an increase of 2.1 C degrees. Doubling the concentration again (from 160 to 320 ppmv), the model calculates a temperature change of **[(*0.5*)(*2.2*)(*15.4*)]** C degrees.

14. Assume this change in temperature with a doubling of CO_2 is representative of other model runs that double CO_2 concentrations. With this assumption, we can anticipate that if Earth's current atmosphere CO_2 concentration of 390 ppmv were doubled to 780 ppmv, Earth's near-surface temperature would increase at least **[(*0.5*)(*2*)(*15*)]** C degrees.

Summary

Some gases in the atmosphere, including H_2O, CO_2, CH_4, and N_2O, absorb IR rising from Earth's surface in a variety of wavenumber bandwidths unique to each gas. The absorbed energy is subsequently emitted in random directions with half directed downward and half upward. This trapping of heat energy in Earth's climate system is the greenhouse effect.

The amount of carbon dioxide in the atmosphere is increasing and its impacts as a greenhouse gas are increasing (although less efficiently). Comparison of IR spectra of CO_2 at different concentrations in the laboratory reveals the relative sensitivities of different wavenumbers to IR absorption and the broadening of absorption wavenumber bandwidths as concentrations increase. Increasing the CO_2 concentration means increasing absorption of IR and resulting temperature increases.
Changing the proportion of atmospheric CO_2 in a global climate model reveals a generalization concerning the effect of doubling the amount of CO_2 on temperature change. Doubling the CO_2, whether it is from 10 to 20 ppmv, 200 to 400 ppmv, or another doubling, produces about the same temperature change. That is, the lower the residual concentration of CO_2 in the atmosphere, the greater the greenhouse effect of a concentration increase.

This investigation centered on CO_2 as a greenhouse gas. However, other greenhouse gases exhibit the same general attributes. This is why gases such as CH_4 and N_2O, which occur in far smaller concentrations in the atmosphere, are much more efficient absorbers of IR and explains partially why H_2O, at much higher concentrations, is a less efficient absorber of IR.

Acknowledgement:

The carbon dioxide spectroscopy animation video was created by Prof. George Lisensky, Chemistry Department, Beloit College, Beloit, WI, from actual infrared spectra for those CO_2 concentrations. Used by permission: Copyright ChemConnections (*http://chemistry.beloit.edu*).