CLIMATE CHANGE AND AVIATION

Climate Changes:

1. Temperature increase
2. Change in precipitation
3. Frequency and intensity of convective weather
4. Strengthening of Jet Stream
5. Changes in wind patterns
6. Sea-level rise
7. Increased storm surge

Air Transportation System Components

1. Infrastructure – Airports (runways, taxiways, gates)
2. Infrastructure – ANSP (surveillance "radar", navigation aids, communication networks)
3. Aircraft Performance
4. Aircraft Safety/Passenger Travel Comfort
5. Local – Noise
6. Local – Air & Water Quality
7. Passenger Demand

The Earth's Climate System

Source: http://eesc.columbia.edu/courses/ees/climate/lectures/radiation/

Introduction

Climate refers to the average or typical state of the weather at a particular location and time of year. The state of the weather is defined by variables such as temperature, humidity, windiness, cloudiness, precipitation, visibility etc., and also the expected range of the deviations of these variables from the mean.

The Earth's Climate is the state of the Earth's habitable environment.

The Earth's Climate System

The Earths climate is the result of complex interactions between system components:

- The atmosphere, the fast responding medium which surrounds us and immediately affects our condition.
- The hydrosphere, including the oceans and all other reservoirs of water in liquid form, which are the main source of moisture for precipitation and which exchange gases, such as CO_2, and particles, such as salt, with the atmosphere.
- The land masses, which affect the flow of atmosphere and oceans through their morphology (i.e. topography, vegetation cover and roughness), the hydrological cycle (i.e. their ability to store water) and their radiative properties as matter (solids, liquids, and gases) blown by the winds or ejected from earth's interior in volcanic eruptions.
- The cryosphere, or the ice component of the climate system, whether on land or at the ocean's surface, that plays a special role in the Earth radiation balance and in determining the properties of the deep ocean.
- The biota - all forms of life - that through respiration and other chemical interactions affects the composition and physical properties air and water.

The atmosphere plays the role of the efficient communicator. The atmosphere is capable of quickly moving and distributing mass and heat over large distances, horizontally and vertically and spread the effect of frequent perturbations to remote regions of the globe within hours to days from their occurrence.

The atmosphere directly affects life on Earth by supplying the gases for the respiration of vegetation and animals and by moving water from oceanic regions to be deposited in liquid or solid form on land.

The atmosphere also shelters life on Earth from the extreme and potentially harmful effects of direct solar radiation.

The oceans are most important because of their tremendous heat storage potential and their ability to distribute that heat horizontally. The composition and motion of the water in the hydrosphere sustains a rich and diverse life system.

The exchange of gases and heat between oceans and atmosphere determines the physical properties and composition of both these sub-systems and is one of the primary climate processes.

Solar Radiation

Solar radiation is the primary energy source for Earth and its climate system.

- properties of the Sun and its energy
- laws governing the transfer of this energy through space from the Sun to the Earth.
- transformation of this solar energy on Earth
- how this energy shapes the properties of Earth's climate.

The Earth Radiation Budget

Energy from the Sun.

The energy that drives the climate system comes from the Sun.

When the Sun's energy reaches the Earth it is partially absorbed in different parts of the climate system. **The absorbed energy is converted back to heat**, which causes the Earth to warm up and makes it habitable.

Solar radiation absorption is uneven in both space and time and this gives rise to the intricate pattern and seasonal variation of our climate.

- relationship between Earth and the Sun throughout the year,
- physical laws governing radiative heat transfer
- develop the concept of radiative balance
- explore the implications of all these for the Earth as a whole

We examine the relationship between solar radiation and the Earth's temperature, and study the role of the atmosphere and its constituents in that interaction, to develop an understanding of the topics such as the "seasonal cycle" and the "greenhouse effect".

The Sun and its Energy.

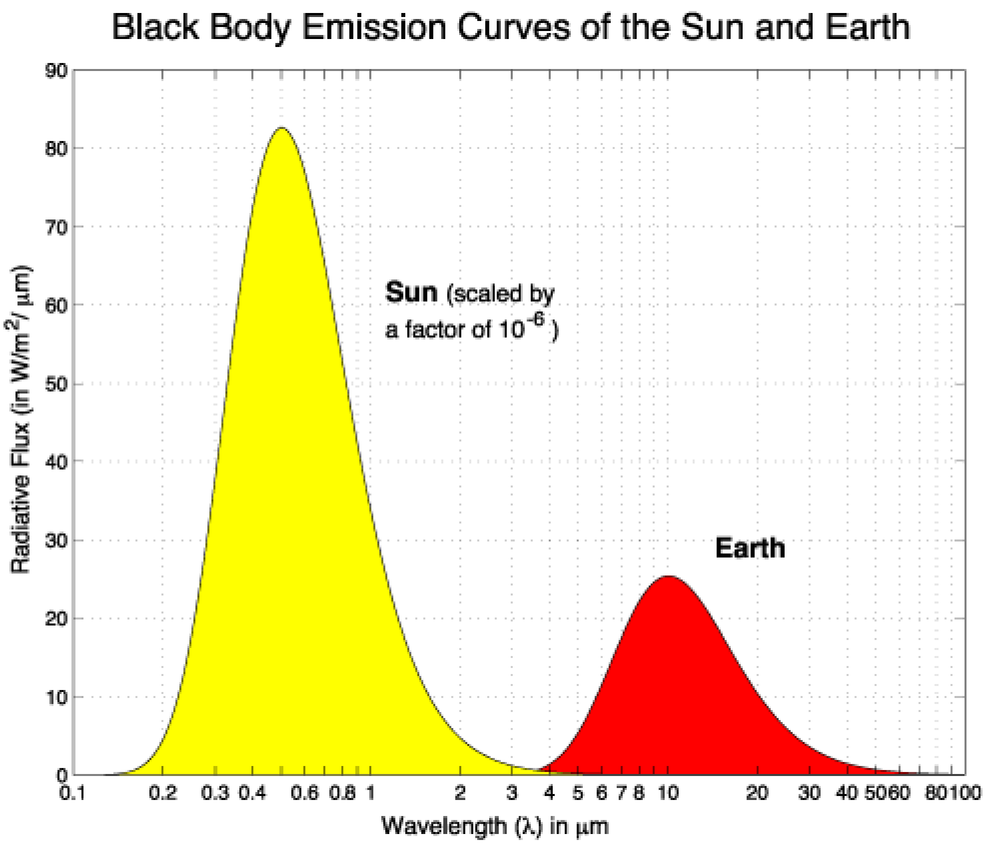
The Sun is the star located at the center of our planetary system.

The Sun is composed mainly of hydrogen and helium.

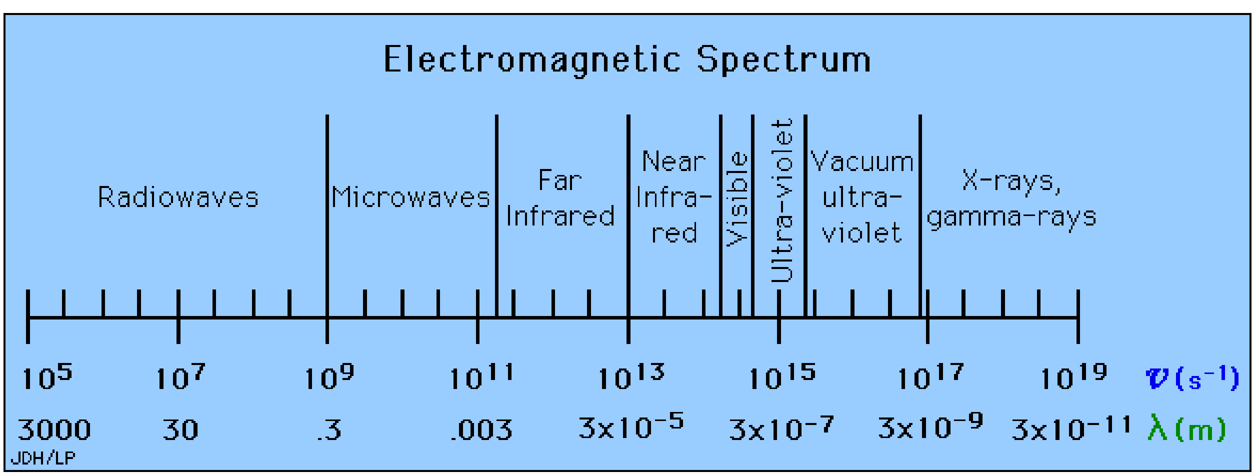
In the Sun's interior, a **thermonuclear fusion reaction** converts the hydrogen into helium releasing huge amounts of energy. The energy created by the fusion reaction is converted into **thermal energy (heat)** and raises the temperature of the Sun to levels that are about twenty times larger that of the Earth's surface.

The solar heat energy travels through space in the form of **electromagnetic waves** enabling the transfer of heat through a process known as **radiation**.

Solar radiation occurs over a wide range of **wavelengths**. The energy of solar radiation is not divided evenly over all wavelengths but, is sharply centered on the wavelength band of 0.2-2 micrometers (μm=one millionth of a meter).



The main range of solar radiation includes **ultraviolet** radiation (**UV**, 0.001-0.4 μm), **visible** radiation (light, 0.4-0.7 μm), and **infrared** radiation (**IR**, 0.7-100 μm).



The physics of radiative heat transfer.

Review of the physical laws governing the transfer of energy through radiation:

- The radiative heat transfer process is *independent* of the presence of matter. It can move heat even through empty space.

- All bodies emit radiation and the wavelength (or frequency) and energy characteristics (or spectrum) of that radiation are determined by the body's temperature.
- The energy flux drops as the square of distance from the radiating body.
- Radiation goes through a transformation when it encounters other objects (solid, gas or liquid). That transformation depends on the physical properties of that object and it is through this transformation that radiation can transfer heat from the emitting body to the other objects.

Radiation transfer from Sun to Earth.

Properties of Solar radiation: The Sun is located at the center of our Solar System, at a distance of about **150 x 10^6 kilometers** from Earth.

With a surface temperature of 5780 K (degrees Kelvin = degrees C + 273.15), the energy flux at the surface of the Sun is approximately **63 x 10^6 W/m^2**

This radiative flux maximizes at a wavelength of about **0.5 *μm*** which is at the center of the visible part of the spectrum.

Solar radiation on Earth:

As the Sun's energy spreads through space its spectral characteristics do not change because space contains almost no interfering matter.

The energy flux drops monotonically as the square of the distance from the Sun. Thus, when the radiation reaches the outer limit of the Earth's atmosphere, several hundred kilometers over the Earth's surface, the radiative flux is approximately**1360 W/m^2**

Effect of orbit's shape:

The **radiation at the top of the atmosphere varies by about 3.5% over the year**, as the Earth spins around the Sun. This is because the Earth's orbit is not circular but elliptical, with the Sun located in one of the foci of the ellipse.

The Earth is closer to the sun at one time of year (a point referred to as **perihelion**) than at the "opposite" time (a point referred to as **aphelion**). The time-of-year when the Earth is at perihelion moves continuously around the calendar year with a period of 21,000-years.

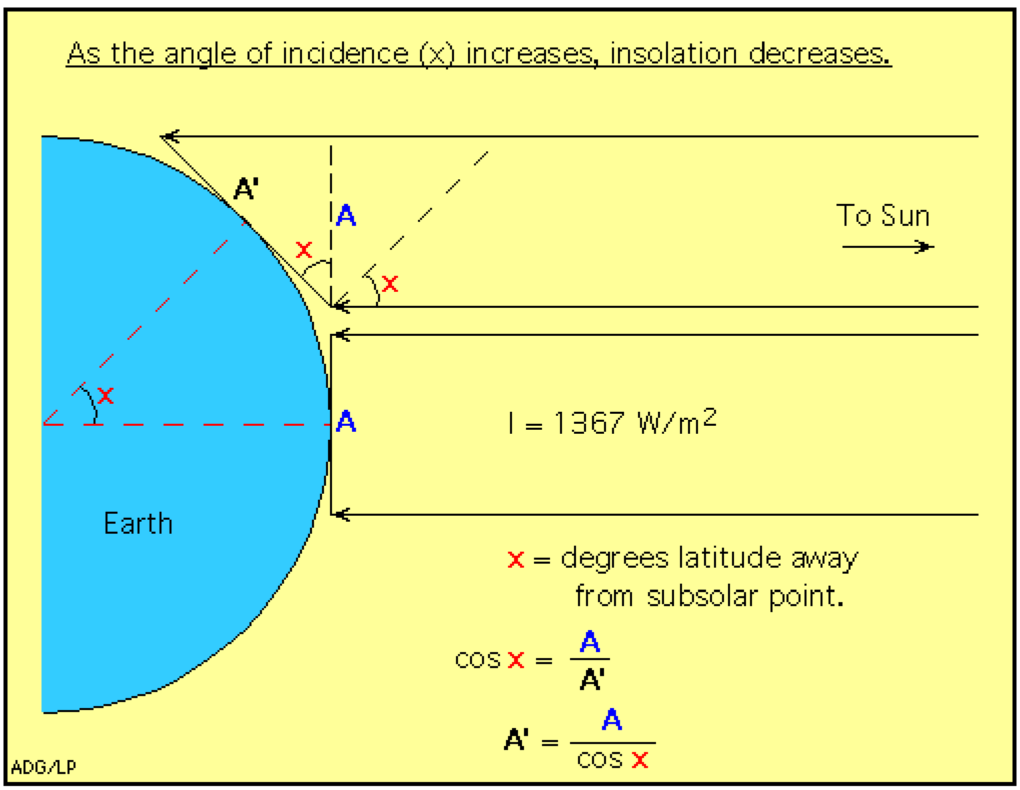
At present perihelion occurs in the middle of the Northern Hemisphere winter. The annual average radiative solar flux at the top of the Earth's atmosphere (=1360 W/m^2) is sometimes referred to as the **Solar Constant** because it has changed by no more than a few percent over the recent history of the Earth (last few hundred years).

There are however important variations in this flux over longer, so-called "geological", time scales, to which the Earth glaciation cycles are attributed.

Effect of Earth's spherical shape:

If the Earth were a disk with its surface perpendicular to the rays of sunlight, each point on it would receive the same amount of radiation, an energy flux equal to the solar constant.

However, the Earth is a sphere and aside from the part closest to the sun, where the rays of sunlight are perpendicular to the ground, **its surface tilts with respect to the incoming rays** of energy with the regions furthest away aligned in parallel to the radiation and thus receiving no energy at all.



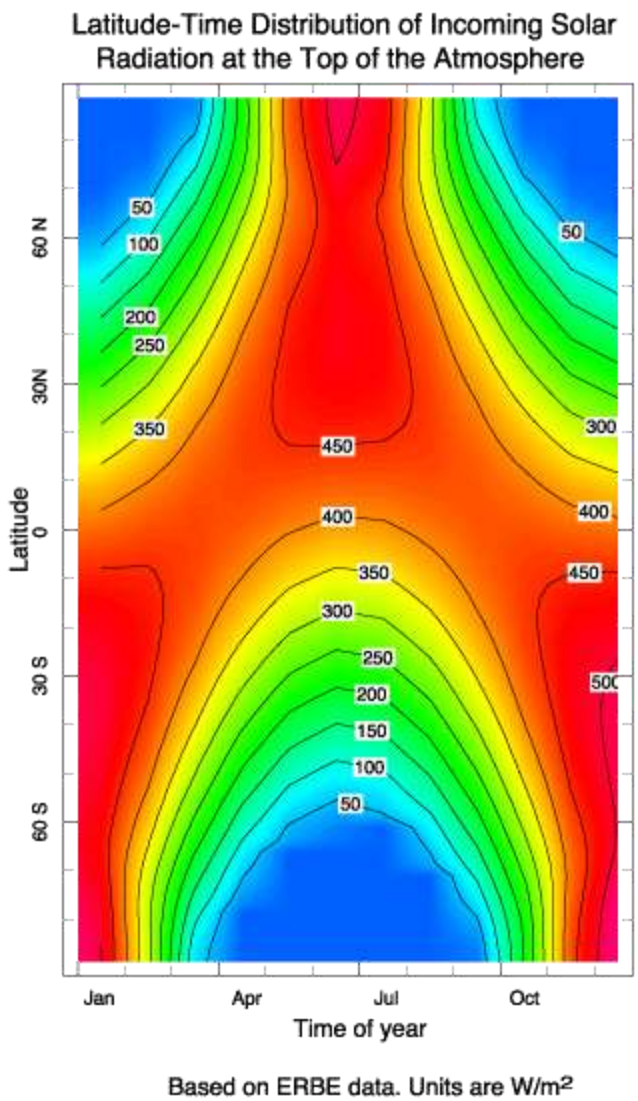
The tilt of the Earth's axis and the seasons:

If the axis of Earth was perpendicular to the plane of its orbit (and the direction of incoming rays of sunlight), then the **radiative energy flux would drop as the cosine of latitude as we move from equator to pole**.

However the **Earth axis tilts at an angle of 23.5° with respect to its plane of orbit**, pointing towards a fix point in space as it travels around the sun. Once a year, on the Summer Solstice (on or about the 21st of June), the North Pole points directly towards the Sun and the South Pole is entirely hidden from the incoming radiation. Half a year from that day, on the Winter Solstice (on or about the 21st of December) the North Pole points away from the Sun and does not receive any sunlight while the South Pole receives 24 hours of continued sunlight.

During Solstices, incoming radiation is perpendicular to the Earth surface on either the **latitude of Cancer** or the **latitude of Capricorn**, 23.5° north or south of the equator, depending on whether it is summer or winter in the Northern Hemisphere, respectively.

During the spring and fall (on the Equinox days, the 21st of March and 23rd of September) the Earth's axis tilts in parallel to the Sun and both Polar Regions get the same amount of light. At that time the radiation is largest at the true equator. Averaged over a full 24-hour period, the amount of incoming radiation varies with latitude and season as shown in below.

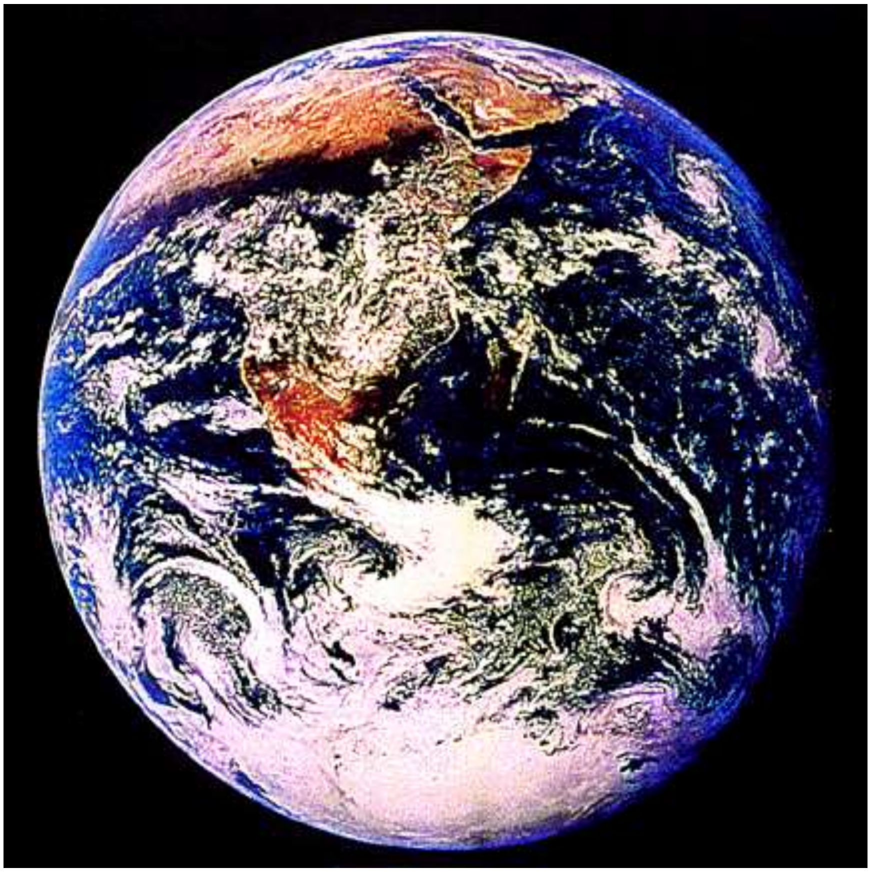


Note that the figure combines the effect of the change in incidence angle with latitude and time of year and the number of hours of sunlight during the day. At the poles, during solstice, the earth is either exposed to sunlight over the entire (24-hours) day or is completely hidden from the Sun throughout the entire day. This is why the poles get no incoming radiation during their respective winter or more than the maximum radiation at the equator during their respective summer.

Energy from Earth and Earth's temperature.

The Earth's albedo.

The Earth's surface reflects part of the solar energy (i.e. returns the radiation back to space in more or less the same spectrum). This is what makes the part of the Earth lit by the sun visible from space in the same way that the moon and the other members of the solar system are visible to us, despite their lack of an inner source of visible radiation.



The most obvious aspect of the Earth as seen from Space is the **brightness of the Earth's cloud cover**.

A significant part of the Earth's reflectivity can be attributed to clouds (this is but one reason why they are so important in the Earth's climate).

The reflectivity of a planet is referred to as the **albedo** (that is, albedo = reflectivity) and is expressed as a fraction.

The albedo of Earth depends on the geographical location, surface properties, and the weather.

On the average however, the **Earth's albedo is about 0.3**. This fraction of incoming radiation is reflected back into space. The other 0.7 part of the incoming solar radiation is absorbed by our planet.

Effective temperature.

By absorbing the incoming solar radiation, the Earth warms up, like a black body and its temperature rises.

If the Earth would have had no atmosphere or ocean, as is the case for example on the moon, it would get very warm on the sunlit face of the planet and much colder than we experience presently, on the dark side (the little warmth on the dark side would come from the limited amount of heat stored in the ground from the previous daytime - this is, to some extent, what we experience in a cloud-free, land locked desert climate).

A**ll heated objects must emit electromagnetic radiation**, particularly so if they are surrounded by empty space. This radiation is referred to as **outgoing**.

As long as the incoming radiative flux is larger than the outgoing, the radiated object will continue to warm, and its temperature will continue to increase. This in turn will result in an increase in the outgoing radiation (according to the **Stefan-Boltzman law** the outgoing radiation increases faster than the temperature).

At some point the object will emit as much radiation as the amount incoming and a **radiative equilibrium** (or balance) will be reached. Using what we have learned about radiative heat transfer and some geometric calculation we can calculate the **equilibrium temperature** of an object if we know the amount of incoming energy.

<u>The case of a planet rotating around the Sun:</u>

The solar radiative flux at the top of the planets atmosphere is defined by $\mathbf{S}_o$ (for solar constant)

The albedo of the planet by**a**.

The total amount of radiation absorbed by the planet. To overcome the difficulty posed by the fact that the planets are spherical and their surface tilts with respect to the incoming radiation, note that the amount distributed over the sphere is equal the amount that would be collected on the planets surface if it was a disk (with the same radius as the sphere), placed perpendicular to the sunlight. If the planet's radius is **R** the area of that disk is πR^2. Thus:

$$\textbf{heat absorbed by planet} = (1 - a)\,\pi R^2 S_o$$

The total heat radiated from the planet is equal to the energy flux implied by its temperature, T_e(from the Stefan-Boltzman law) times the entire surface of the planet or:

$$\textbf{heat radiated from planet} = (4\pi R^2)\,\sigma T^4$$

In radiative balance we thus have:

$$(4\pi R^2)\,\sigma T_e^4 = (1 - a)\,\pi R^2 S_o$$

Solving this equation for temperature we obtain:

$$T_e = [(1\text{-}Aa)S_o / 4\sigma]^{1/4}$$

A subscript **e** to the temperature to emphasize that this would be the temperature at the surface of the planet if it had no atmosphere. It is referred to as the **effective temperature** of the planet.

According to this calculation, the effective temperature of Earth is about 255 K (or -18 °C). With this temperature the Earth radiation will be centered on a wavelength of about 11 μm, well within the range of infrared (IR) radiation.

Because of the spectral properties of the Sun and Earth radiation we tend to refer to them as "**shortwave**" and "**longwave**" radiation, respectively.

The greenhouse effect.

The effective temperature of Earth is much lower than what we experience.

Averaged over all seasons and the entire Earth, **the surface temperature of our planet is about 288 K (or 15°C)**.

This **difference is in the effect of the heat absorbing components** of our atmosphere. This effect is known as the **greenhouse effect**, referring to the farming practice of warming garden plots by covering them with a glass (or plastic) enclosure.

How does the greenhouse effect work?

The Earth's atmosphere contains many trace components.

COMPOSITION OF EARTH'S ATMOSPHERE (BY NUMBER OF MOLECULES, %)

Major constituents:

N_2 (78.1) **O_2** (20.9)

Active minor constituents:

H_2O (0.48) **CO_2** (0.035) **O_3** (0.000007)

CH_2 (0.00017) **N_2O** (0.00003) **CFC's** (0.00000014)

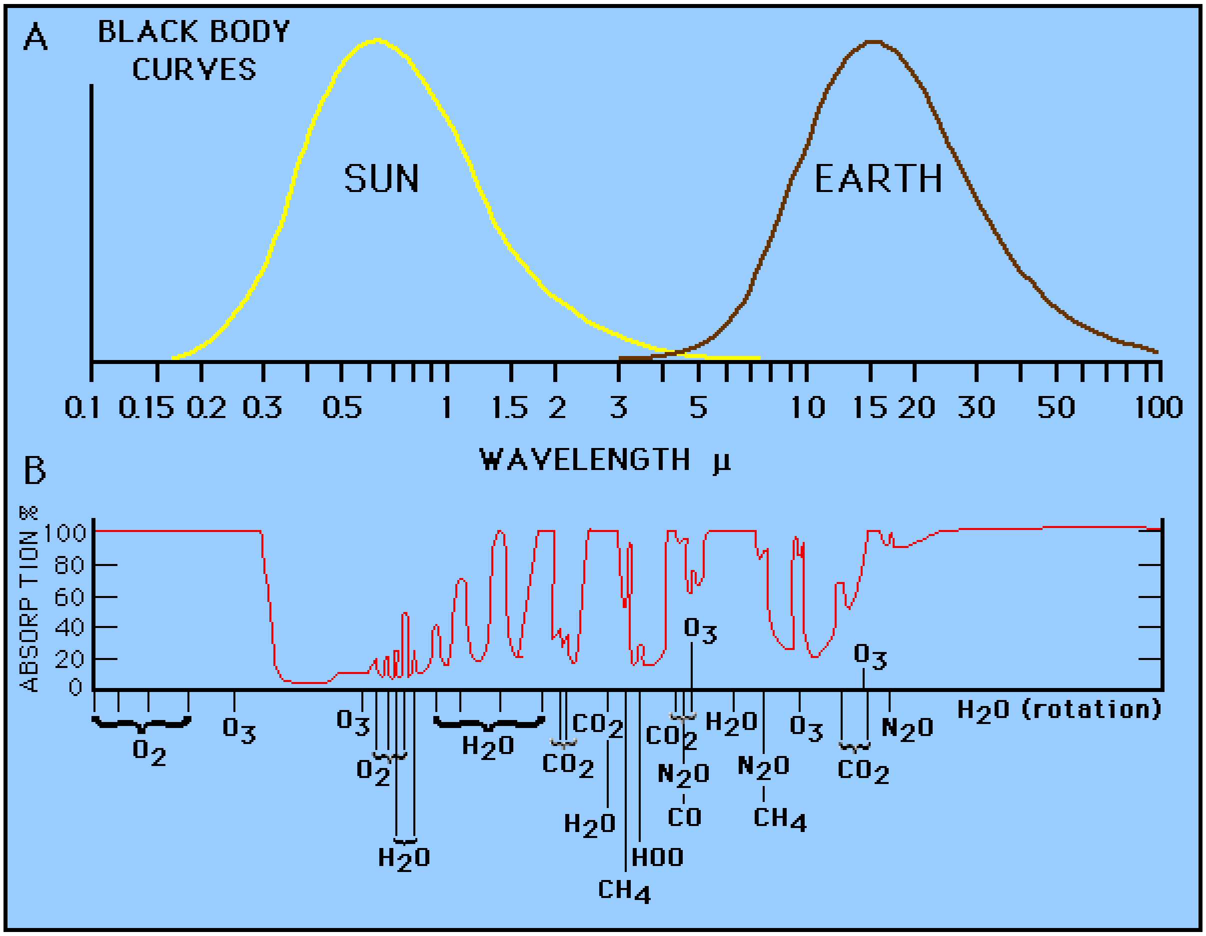
H_2O liq.+ice (0.002) **aerosols** (0.00000002)

Inactive minor constituents:

Ar (0.93) **Ne** (0.0018)

He (0.00052) **Kr** (0.00010)

While the major atmospheric components (Nitrogen and Oxygen) absorb little or no radiation, some of the minor components are effective absorbers. Particularly effective is **water vapor**, which absorb effectively in the IR wavelength range.



Because the atmosphere is almost transparent to sunlight, all that is absorbed at the surface results in warming and the emission of IR radiation; **this radiation cannot freely escape into space because of absorption in the atmosphere by trace gases such as water vapor and carbon dioxide (CO_2)**.

These absorbing gases and their surrounding air warm up, emitting radiation downward, towards the Earth's surface, as well as upward, towards space. **This effectively traps part of the IR radiation between ground and the lower 10 km of the atmosphere**.

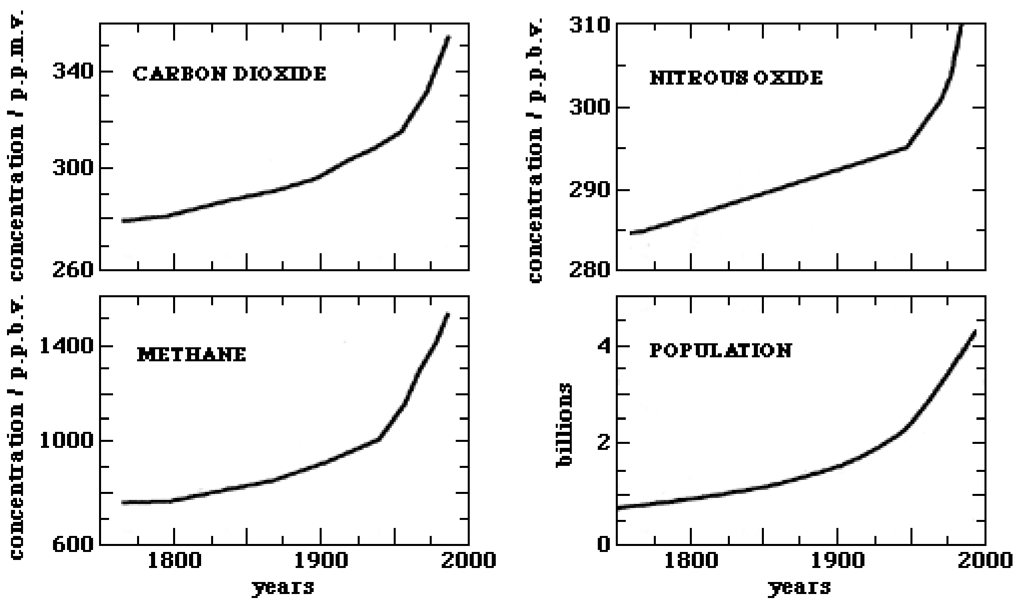
This reduction in the efficiency of the Earth to lose heat causes the surface temperature to rise above the effective temperature calculated above ($\mathbf{T_e}$) until finally, enough heat is able to escape to space to balance the incoming solar radiation. The effect is analogous to that of a blanket that traps the body heat preventing it from escaping into the room and thus keeps us warm on cold nights.

All that the IR absorbing gases do is make it more difficult for heat to escape, they don't (and can't) stop the heat output, because half of their emission is directed upward towards space.

The greenhouse effect forced the planet to raise its surface temperature until the amount of heat radiated from the top of the absorbing layer is equal to the solar radiation at the top of the atmosphere. It is at the top of the absorbing layer that the effective temperature is reached, while down at the surface of the Earth it is much warmer.

GREEN HOUSE GASES

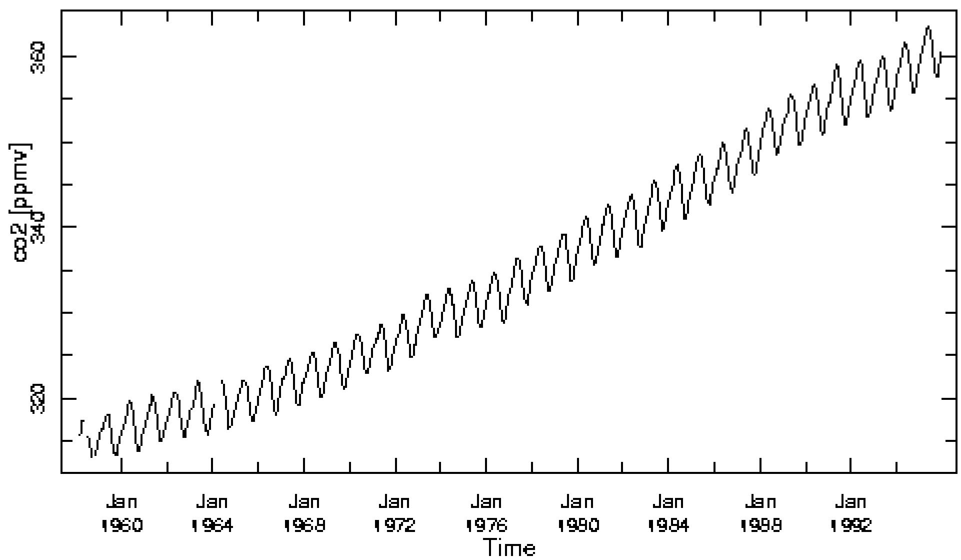
Rates of increase of individual greenhouse gases



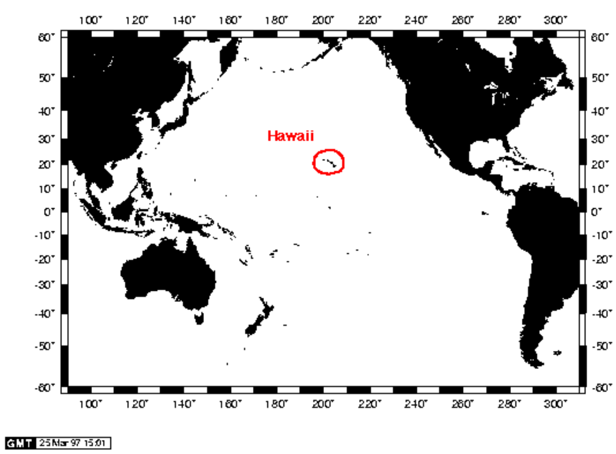
Increase of greenhouse gas concentrations over the last 200 years from antarctic ice cores. CO_2 (from Oeschger & Siegenthaler 1988), CH_4 (from Pearman et al. 1986), N_2O (from Khalil & Rasmussen 1988). The population growth is included for comparison.

Adapted from: Lorius, Claude, Jean Jouzel, and Dominique Raynaud (1992) The ice core record: past archive of the climate and signpost to the future. In: *Antarctica and Environmental Change*, (ed. D.J. Drewry, R.M. Laws, and J.A. Pyle) pp. 27-34, New York: Oxford University Press.

Mauna Loa CO_2 record



1. one of the most important environmental monitoring efforts
2. Mauna Loa, Hawai, US Weather Bureau research station far away from CO_2 sources
3. record started in 1958, until present
    a. seasonal variations (5ppm)
    b. overall increase (1980s): 0.5%/y
4. record can be extended into the past by using the ice core archive: CO_2 increased from 1700 to today from 280ppm to 360ppm



Solar Radiation, Earth's Atmosphere, and the Greenhouse Effect.

Topics covered:

1. different ways radiant energy can interact with matter.
2. How energy is transferred from radiant energy to matter and visa versa.
3. What processes control the shape of the vertical temperature profile of the atmosphere between the ground surface and 100 km above the surface.
4. Why the sky is blue and Sunsets are red

I. Interaction of electromagnetic radiation with matter.

A. Radiant energy can interact with matter in three ways. Most often its behavior is a combination of two or more of these modes, but for the sake of explanation we will look at them individually.
    A. If matter does not interact with the incident radiation, that is, there is no change in the matter because of the radiant energy that strikes it and it does not let the energy pass through it (i.e. it is opaque to the radiant energy), then it ***reflects*** the energy. Reflection only changes the direction of the beam of radiant energy, not its wavelength or amplitude.
    B. If matter allows radiant energy to pass through it unchanged, the matter is described as ***transparent*** to the incident radiation. Again, as with reflection, there is no change in any of the properties of the radiant energy.
    C. On the other hand, if there is some interaction between the incident radiation and the matter (e.g. some energy is transferred from the radiant beam to the matter resulting in an increase in molecular energy of the matter), then we describe this transfer of energy from the radiant beam to the matter as ***absorption***.

B. Black bodies by definition absorb and re-radiate radiant energy equally and completely at all wavelengths they intercept. Thus, as a perfect reflector reflects all radiation it intercepts, and a perfectly transparent substance transmits unchanged all radiant energy striking it, so a black body absorbs all radiation that it intercepts.

    Gases on the other hand are not black bodies; they absorb and re-radiate only at very specific wavelengths. Our atmospheric gases absorb different narrow bands of incoming solar radiation. Each absorption band is a response to a different mechanism of energy transfer. The smaller molecules of oxygen and nitrogen absorb very short wavelengths of solar radiation while the larger molecules of water vapor and carbon dioxide absorb primarily longer infrared radiant energy.

Effect of Earth's atmosphere on incoming solar radiation.

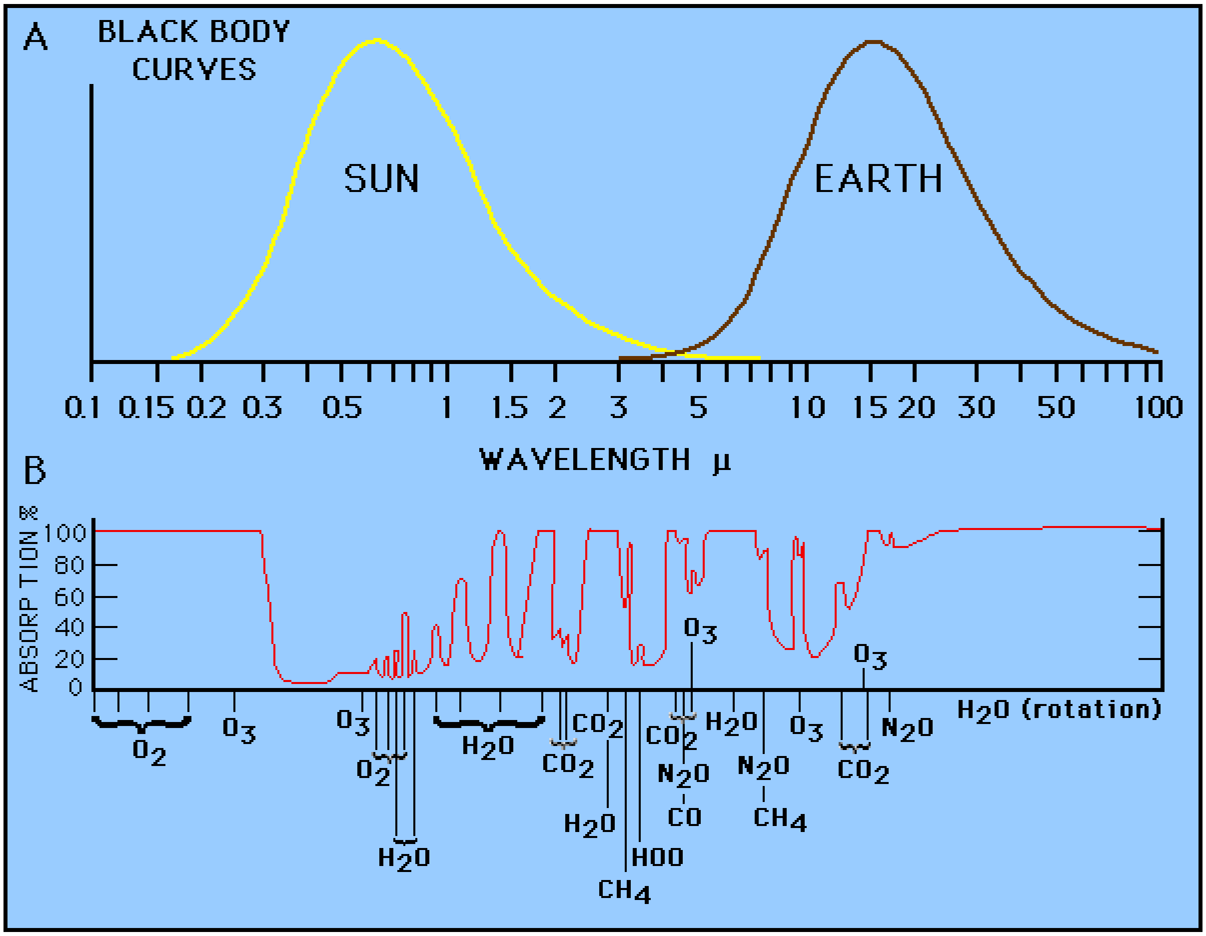
A. Reflectivity: 35% of incoming solar radiation is reflected back to space.
   1. Clouds; Twenty-four percent of incoming solar radiation is reflected by clouds, 4% by the Earth's surface.
   2. Scattering; Seven percent of incoming solar radiation is scattered back to space. Particles in the atmosphere can scatter incoming solar radiation. This process works as follows: a particle momentarily traps some part of the solar spectrum that strikes it and then releases that same energy in all directions. Consequently one half of the radiation scattered is returned to space and the other half is sent down to the Earth's surface.

      The wavelengths scattered depends on the size of the scattering particle. Haze and smog particles are relatively large and they scatter all wavelengths. The presence of particles of smog and haze (small water droplets) gives the sky a milky appearance. Contrast the color of the sky on a hot humid summer day with its appearance on a cold clear winter day.

      Small particles, such as air molecules (molecules of nitrogen or oxygen), scatter a larger proportion of short wavelength light (blue and violet) rather than longer wavelengths (red). This preferential scattering of blue light is what gives the sky its blue color. This effect is also responsible for red Sunsets. At Sunset, if you look directly at the Sun, the Suns rays have traveled through a much greater thickness of the Earth's atmosphere than they do when the Sun is directly overhead at noon. Consequently, because of the preferential scattering of blue light by the atmosphere, only red and yellow light reach your eyes, hence red Sunsets.

B. Absorption: about 17% of incoming solar radiation is absorbed at various levels in the atmosphere.

1. The shortest wavelengths of the solar spectrum, the ultraviolet $< .12$ microns are absorbed by oxygen and nitrogen in the upper atmosphere above 100 kilometers.
2. UV radiation between between .12 and .18 microns are absorbed by oxygen above 50 kilometers.
3. UV radiation between .18 and .34 microns are absorbed between 50 kilometers and 10 kilometers by ozone.
4. The atmosphere is nearly transparent to visible radiation between .34 and .7 microns.
5. The infrared part of the solar spectrum is partially absorbed by water vapor in the troposphere below 10 kilometers.



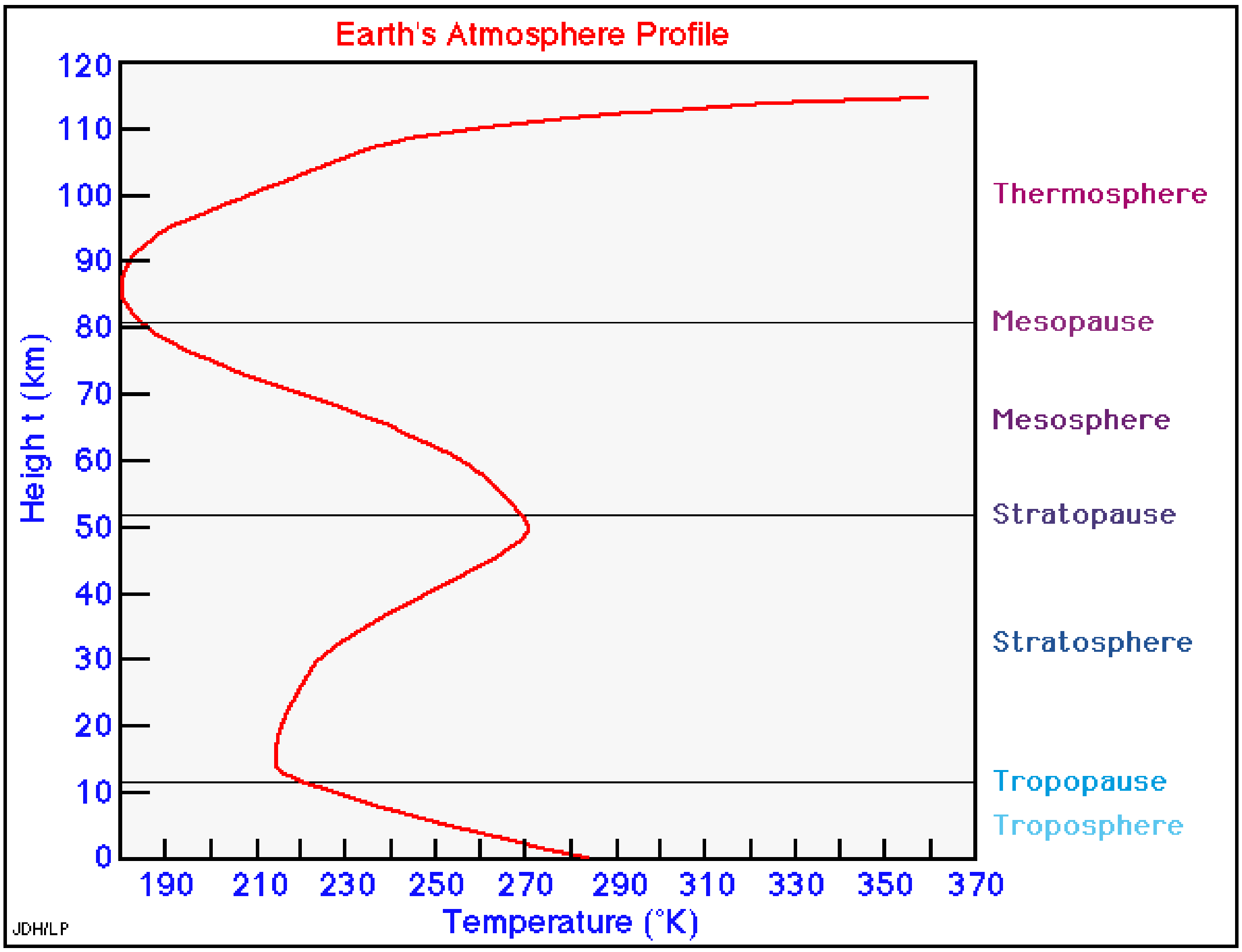
Absorption is the process by which radiant energy is transferred to matter.

If the matter is a gas, radiation can effect it in a number of ways. The ways it can absorb energy depends on the size and complexity of the gas molecule. The gas molecule can be rotated and a variety of vibratory modes can be excited depending on the nature of the molecule. If the energy is strong enough the molecule can be broken apart. Each mode of energy absorption occurs at a specific narrow band of the solar spectrum. Gases, therefore, are not like black bodies that absorb equally and completely at all wavelengths. Rather, they absorb only at specific, often narrow ranges of wavelengths. Diatomic molecules such as nitrogen and oxygen (most of our atmosphere) can absorb energy by increasing the vibration of the bond between the two atoms.

If the energy absorbed is great enough it may break the bond resulting in two free wheeling oxygen or nitrogen atoms traveling at high speeds.

O_2 + ultraviolet light = O + O

This occurs in the uppermost regions of the atmosphere, above one hundred kilometers.



The most energetic (shortest wavelength) part of the solar spectrum is involved in this process. Nitrogen absorbs only in the extreme ultraviolet of which there is very little in the Sun's radiation. Oxygen absorbs more strongly than nitrogen and over a wider range of wavelengths in the ultraviolet. Oxygen molecules are therefore broken into oxygen atoms in the highest regions of the atmosphere. By an altitude of about 100 kilometers much of the radiation that is energetic enough to do this breaking of molecular bonds is used up and this process diminishes. Hence their is heating of the uppermost atmosphere (fast moving atoms of nitrogen and oxygen) and as the altitude decreases to about one hundred kilometers the atmosphere cools. For some distance above and below 80 kilometers there is little absorption of solar energy and consequently little heating of the atmosphere so the temperature reaches a minimum.

Descending below eighty kilometers the atmosphere is heated by another process. Here the atmosphere gets denser (thicker) with decreasing altitude; the molecules of oxygen and nitrogen are closer together. Now if the bond of an oxygen molecule is broken and the two atoms go flying off, there is a higher likelihood that one of these atoms will strike an oxygen molecule. If it does it may form an ozone molecule. Above 50 kilometers the heating is primarily due to the break up of oxygen molecules by ultraviolet radiation with wavelengths between .12 and .18 microns, while between 50 kilometers and 10 kilometers the heating is due to the absorption by ozone of ultraviolet radiation with wavelengths between .18 and .34 microns.

$$O + O_2 = O_3$$

Ozone can in turn be broken up by ultraviolet light resulting in this reaction:

$$O_3 + \text{ultraviolet light} = O_2 + O$$

Both the breaking up of oxygen molecules above fifty kilometers and ozone molecules at fifty kilometers and below causes heating of the atmosphere that peaks at about 50 kilometers (the stratopause). Between 50 and 10-15 kilometers (the stratosphere) the solar energy energetic enough to break up ozone (ultraviolet radiation) is used up and the atmosphere cools.

Effect of atmosphere on Earth radiation.

A. Below ten kilometers the atmosphere warms in a linear way to the Earth's surface. This final heating is dominated not by solar radiation but rather by radiation from the Earth's surface. The Earth, being much cooler than the Sun, emits much longer wavelength radiation. At a solar temperature of nearly 6000 Kelvin, the peak of solar output is in the visible (light) part of the electromagnetic spectrum while the Earth, at a temperature of 278 Kelvin, emits most of its energy in the infrared (heat) portion of the electromagnetic spectrum.

   Energy of this wavelength cannot be absorbed by tiny oxygen and nitrogen molecules, but it can be absorbed by the larger and more complex molecules of water vapor (H_2O) and carbon dioxide (CO_2). These complex molecules have a number of vibratory and rotational modes which absorbs energy in the infrared portion of the electromagnetic spectrum.

These together with other so called greenhouse gasses (methane CH_4, and nitrous oxide N_2O) cause the Troposphere to warm as the Earth's surface is approached (greenhouse effect). Man can and probably is enhancing this effect by adding to the atmospheric concentration of these greenhouse gasses. Most notably we are enhancing carbon dioxide, which has natural sources in the decay of plant and animal remains, through the burning of fossil carbon. Methane, which has natural sources in swamps and grazing ruminant animals, is being enhanced through the proliferation of rice paddies (artificial swamps) and cattle herds (cattle burp methane, more on that later). The atmosphere, heated by the absorption of Earth radiation by these greenhouse gasses, in turn radiates heat back to the Earth's surface increasing the Earth's surface temperature.

B. Transparency: The Earth's atmosphere is effectively transparent to solar radiation between .34 and .7 microns. Consequently 22.5 percent of incoming solar radiation goes directly to the surface of the Earth and is absorbed.

C. Transfer of radiation through a planet's atmosphere.
   1. A planet and its atmosphere, in our solar system, can radiate back to space only as much energy as it absorbs from incoming solar radiation.

      The solar constant x (1 - the albedo)

   2. The amount of radiation it radiates back to space is determined by its effective temperature.

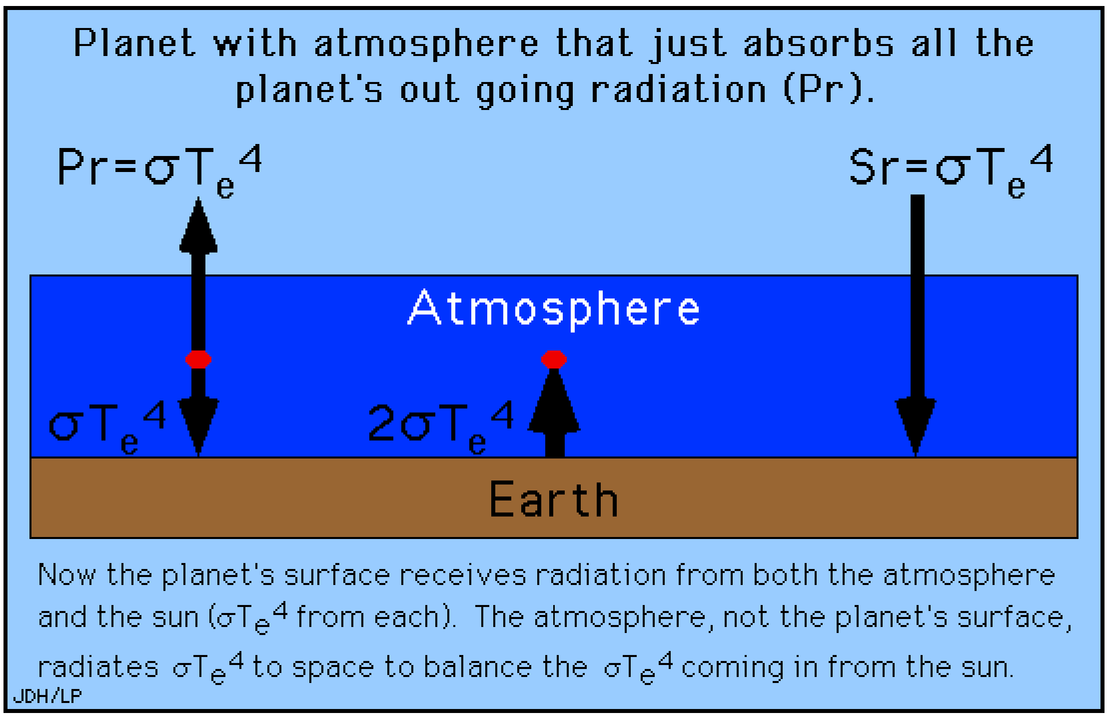
      $$\text{Planetary radiation} = \sigma T_e^4$$

   3. The wavelength of this planetary radiation is determined by the planet's effective temperature.

      $$\lambda = a/T_e \text{ (Wein's Law)}$$

   4. How strongly a planet's atmosphere absorbs the planet's radiation depends on the optical properties of its atmosphere and the nature of the planet's radiation.

5. A planet's atmosphere has a bottom and a top; it radiates both upward and downward.
6. Some atmosphere's are so strongly absorbing that some fraction of the atmospheric thickness can absorb all radiation received from the ground or adjacent atmospheric layers. From now on we will assume the planet does not absorb any incoming solar radiation i.e. the atmosphere is transparent to it.
   a. We can divide such a planet's atmosphere into a series of layers, each layer being just thick enough to absorb all the radiation received from adjacent layers. In this kind of atmosphere, each layer is heated by the overlying and underlying layers or the ground below the lowest layer.



   b. The topmost layer must radiate to space the same amount of energy it receives from the Sun. If this were not the case and the topmost layer radiated less, the planet would heat up, or if it radiated more, the planet would cool off. As a consequence, the planet's temperature will change until it radiates as much as it receives.
   c. The topmost layer will radiate downward as much energy as it radiates upward. Consequently, it must receive from the layer below, or the ground, if it is the lowermost layer, twice as much

energy as it radiates to space (remember, we are assuming this atmosphere is transparent to incoming solar radiation). Think about this. Lets assume that the ground lies below the second layer. How much energy must this second layer receive from the ground? Remember it is receiving energy from the layer above and from the ground below. Keep in mind the conservation of energy law; it makes the problem a lot easier than if energy were not conserved.

d. Think about the surface temperature of a planet that has an atmosphere so strongly absorbing that it can be divided into 5 layers.

Summary

The budget of solar radiation is as follows:

	percent
Reflected	35
Absorbed by atmosphere	17.5
Scattered to the Earth from blue sky	10.5
Scattered to the Earth from clouds	14.5
Radiation going directly to Earth's surface	22.5
	100