Introduction

This section examines the atmosphere as a system, and several atmospheric phenomena that have become critical in the understanding and guardianship of our environment. The current state of the atmosphere is the result of a multitude of facts. The energy from the sun produces the movements or currents in the atmosphere. This energy, the Earth's movement relative to the sun, and the components of the atmosphere and of the Earth's surface maintain the long-term climate, the short-term weather, and the temperature conditions. These provide conditions fit for the forms of life found on Earth. The condition of the physical world affects and is affected by the life present. The entire system is therefore called the biogeochemical system. In the last century especially, this system--which evolved over billions of years--has been subject to rapid changes due to industrial activities increasing at unprecedented rates.

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This unit discusses some of the basic science and details of the interactions involving the atmosphere. We begin by examining the nature of the sun's energy, and the actions and reactions it produces in the atmosphere. We then discuss how industrial activity has perturbed atmospheric conditions, and what policy actions are being taken to reduce our impact. Due to the complexity of the system, there are still large amounts of scientific uncertainty in predicting changes precisely, but we do know enough to describe and project qualitative features of the system that lead to an understanding of the impacts of large scale human activity.

The Earth-Sun Relationship

A look at the Earth-Sun system provides important insight into current environmental phenomena. Since the beginning of the Earth's evolution four and a half billion years ago, the atmosphere and landscape have changed significantly. Today, global atmospheric problems such as global warming and ozone depletion arise from changes in the delicate balance of the Earth's atmosphere that alter the amount of the sun's radiation reaching humans and other living creatures. The Earth's immediate physical environment is patterned by three primary influences:

1. The nearness of the sun.

2. The Earth's atmosphere, a mixture of gases held in a layer surrounding the Earth by the Earth's gravitational force. This layer has reached the current and somewhat steady composition of approximately 80% nitrogen and 20% oxygen over the last four and a half billion years.

3. The composition of the solid mass of the Earth, which gives rise to the materials in and on the Earth (including water, an essential to our type of life). Also resulting from the composition and manner of the origin of the Earth is the temperature of the Earth's core.

This section will focus predominantly on the first two influences: the Earth's atmosphere, and the Earth's relationship to the sun.

From a physical point of view alone, the Earth-Sun system can be represented simply as in Figure 1. The two main forces and effects of the sun on the Earth are the gravitational force (maintaining the Earth in an orbit around the sun), and the electromagnetic radiation from the sun (keeping the Earth's atmosphere at a particular temperature).

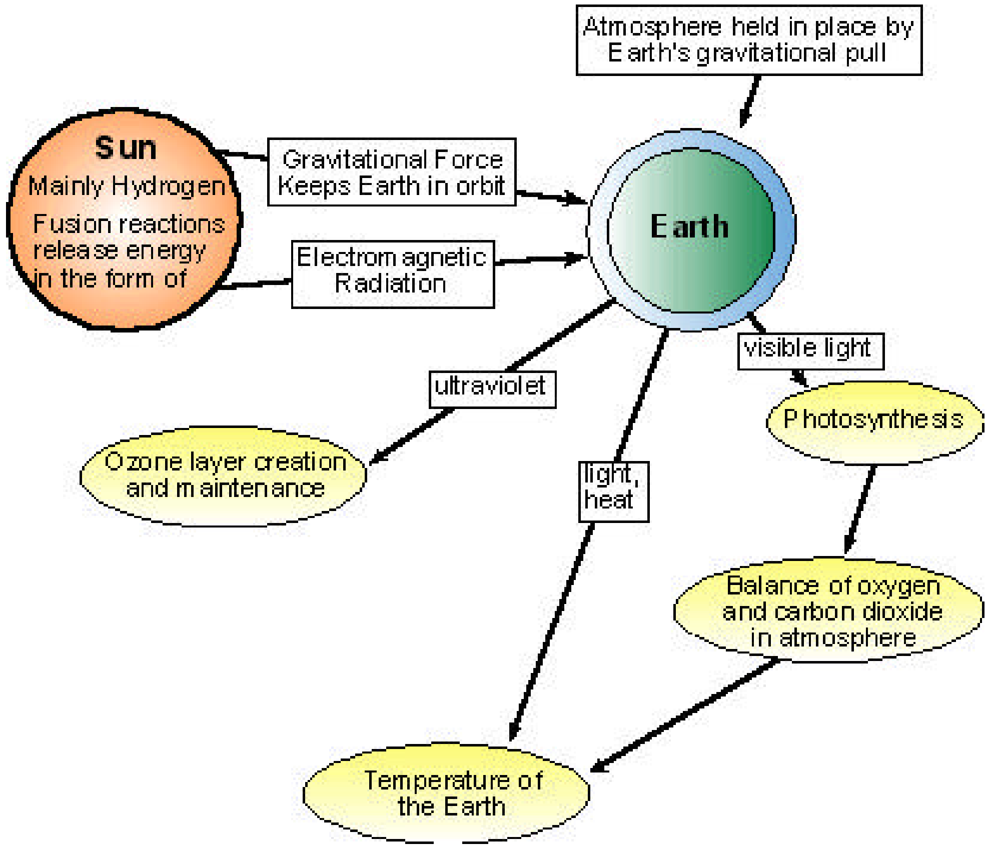

Figure 1: Earth-Sun system with primary influences.

Different components of the sun's (solar) spectrum interact with the atmosphere. Over billions of years, this interaction has produced both the ozone layer and current climatic conditions with feedback from life that evolved. These phenomena form the major topics of this unit. We begin with a description of solar radiation.

The Sun & its Energy

The sun's energy is the primary source of energy for all surface phenomena and life on Earth. Combined with the material of the Earth (including the molecules held close by the Earth's gravitational force called the atmosphere), this energy provides for the immense diversity of life forms that are found on the Earth. We will now look in detail at solar energy and its interplay with the constituents of the Earth's atmosphere.

Characteristics of the Sun

The sun is a medium, yellow star, consisting primarily of hydrogen at temperatures high enough to cause nuclear fusion. Nuclear fusion is a nuclear reaction in which hydrogen nuclei fuse together to form helium nuclei and release energy. In this state, some 120 million tons of matter - mostly hydrogen - are converted into helium on the sun every minute, with some of the mass being converted into energy. The size of the sun determines its temperature and the amount of energy radiated.

Electromagnetic energy from the sun comes to Earth in the form of radiation. The term "radiation" simply denotes the fact that the energy travels as rays, that is, in straight lines. In general, the terms "solar energy" and "solar radiation" simply refer to energy from the sun. Electromagnetic energy is produced when electric charges change their potential energy. It is characterized by the property that it is pure energy, not requiring any matter (or medium) for its existence or movement. Electromagnetic energy can therefore travel through space (which is a vacuum), traveling at a speed that is the same for all forms of electromagnetic energy and is equal to the speed of light, 3×10^8 m/sec (or 186,000 miles per second).

The sun radiates energy equally in all directions, and the Earth intercepts and receives part of this energy. The power flux reaching the top of the Earth's atmosphere is about 1400 Watts/m^2. This measure simply means that on the average, one square meter on the side of the Earth facing the sun receives energy from the sun equal to that from fourteen 100 Watt light bulbs every second!

The sun is in a relatively stable state, and as far as we can tell, will continue to be so for about another three billion years. The sun and other stars do show periods of slightly higher than normal activity, detectable in our sun by an increase in sunspot activity. During sunspot activity, more energy reaches the Earth. The sun spends about a quarter of its time in a state with very few sunspots. It is suspected that the Sun dimmed about ten times in the last 100,000 years causing "Little Ice Ages" (extended periods of unusually cold temperatures) of about a couple of centuries each. The last such quiescent state occurred in the late seventeenth century. The sun has also shone with considerable above-average brightness at least twice in our geological era: about 5,000 years ago, around the time of the beginning of the ancient civilizations of China, Minoa, Sumeria, and the Indus Valley; and about 1,000 years ago, when the temperatures of Northern England rose high enough to allow vineyards to flourish there.

Electromagnetic Spectrum - Basic Science

The entire region of electromagnetic energy distinguished by wavelength and frequency is called the electromagnetic spectrum. The propagation of the energy along the rays is in the form of a wave with the amount of energy alternating between high and low values, as in a water wave. Thus we say that light, heat, etc., travel in the form of waves. Wavelength can be defined as the distance between two successive peaks (or troughs) in waves of energy, while frequency is measured by counting the number of peaks that pass a given point every second.

In the diagrams of the spectra in this section, we use two different scales in measuring wavelengths. The first is microns or micrometers (μm), which is equal to 10-6 meters. The other is nanometers (nm), equal to 10^{-9} meters. In discussing small ranges of the spectrum, we use units of nm, and in discussing the overall spectrum or larger regions, we revert to μm.

Frequency is measured in units of cycles per second, or hertz (Hz). One cycle per second is equal to one hertz.

In order of decreasing frequency (and increasing wavelength), the various regions of the electromagnetic spectrum are: gamma rays, x-rays, ultraviolet, visible light, infrared, microwaves, and radio waves. Electromagnetic energy from the sun consists mostly of a small amount of ultraviolet, all visible light, and some infrared.

The full electromagnetic spectrum is depicted in Figure 2. Table 1 gives the same information, as well as some technological applications.

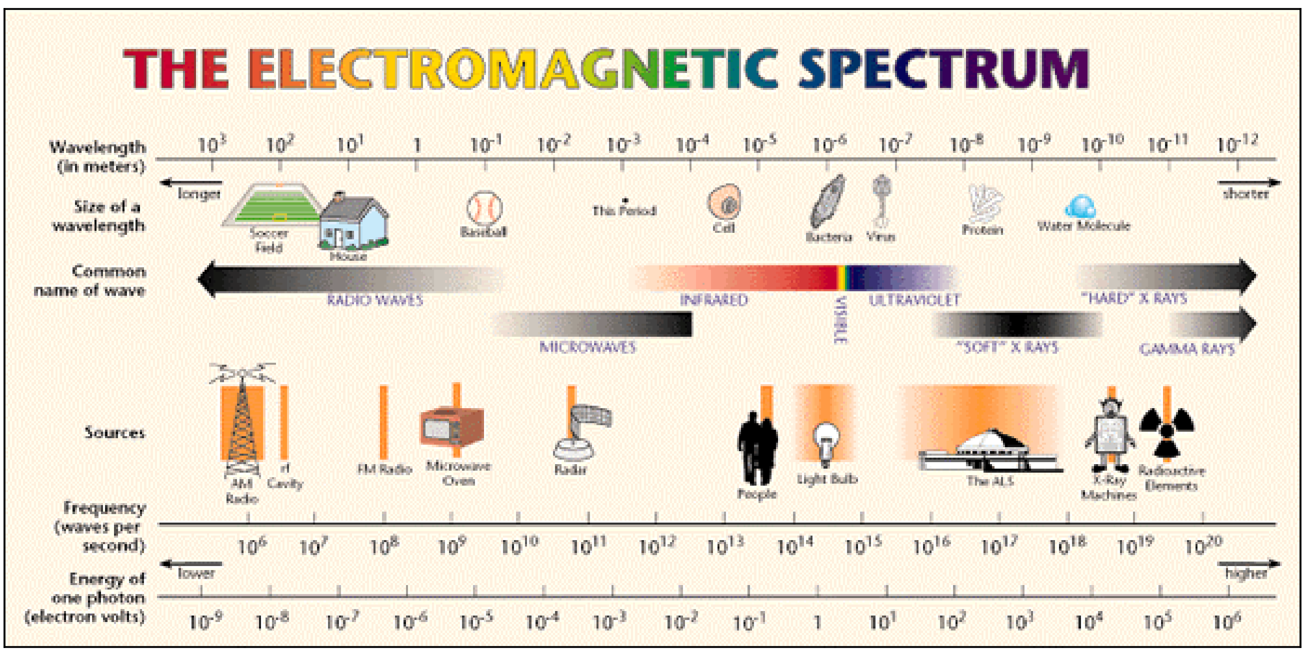

Figure 2: The electromagnetic spectrum.
(from Lawrence Berkeley National Laboratory)

Name of Region	Wavelength Range (in m, µm, and nm)	Frequency Range	Technological Applications / Role in Nature
Gamma Rays	10^{-14} to 10^{-10} m 10^{-8} to 10^{-4} µm 10^{-5} to 10^{-1} nm	$3x10^{22}$ to $3x10^{18}$ Hz	Radiation therapy
X - Rays	10^{-14} to 10^{-8} m 10^{-8} to 10^{-2} µm 10^{-5} to 10 nm	$3x10^{22}$ to $3x10^{16}$ Hz	Radiation therapy; diagnosis (lower frequencies)
Ultraviolet Rays	0-8 to $4x10^{-7}$ m 10^{-2} to 0.4 µm 10^{-5} to 400 nm	$3x10^{16}$ to $0.75x10^{16}$ Hz	Tanning; Promotes production of Vitamin D in human skin; Photosynthesis in plants
Visible Light	$4x10^{-7}$ to $8x10^{-7}$ m 0.4 to 0.8 µm 400 to 800 nm	$0.75x10^{16}$ to $0.375x10^{16}$ Hz	Lamps for seeing (Eyes respond to this range)
Infrared	$8x10^{-7}$ to 10^{-3} m 0.8 to 10^{3}µm 800 to 10^{6} nm	$0.375x10^{16}$ to $3x10^{11}$ Hz	Infrared photography
Radio Waves	10^{-4} to 10^{6} m	$3x10^{12}$ to 300 Hz	Communication devices

Table 1: Regions of the entire electromagnetic spectrum and general applications.
Note that the regions are not strictly delineated.

We have specialized sensory organs that only detect some parts of the spectrum. For example, the eye detects visible light, and even distinguishes different wavelengths within the spectrum of visible light as color! The skin perceives radiation from the infrared region of the spectrum as heat. Note that sound is not a form of electromagnetic energy. Because sound is really the energy of the motion of molecules through a medium (mechanical energy), it cannot travel through a vacuum. As we already noted, electromagnetic energy has no need for a medium through which to travel, and can therefore travel through space from the sun to reach the Earth.

Different molecules absorb different regions of electromagnetic energy preferentially. For example, the water molecule preferentially absorbs certain wavelengths in the microwave region of the electromagnetic spectrum. This preference is the basis of the efficient cooking of food by microwave ovens. Calcium, a primary constituent of bones, absorbs energy in the x-ray region more strongly than do the water or carbon in the cells of ordinary tissue, allowing for the use of x-rays to generate images that show unevenness such as broken bones or tumors. The chlorophyll molecule in green plants absorbs mostly ultraviolet (and also some blue violet, and red light) and uses this energy for photosynthesis. Most of the green light in sunlight is reflected by leaves, making them appear green to our eyes.

Solar Spectrum

The range of electromagnetic energy emitted by the sun is known as the solar spectrum, and lies mainly in three regions: ultraviolet, visible, and infrared. The solar spectrum extends from about 0.29 µm (or 290 nm) in the longer wavelengths of the ultraviolet region, to over 3.2 µm (3,200 nm) in the far infrared. Small amounts of radio waves are also given off by the sun and other stars. In fact, if the sun's image is made from its radio waves, it appears 10% larger than if its image is made from visible light. There are some "cooler" stars that give off mostly radio waves and no visible radiation.

The range of energy given off by a star depends upon the temperature and size of the star. Smaller, hotter stars (called "white dwarfs") give off more energy in the blue region and appear "whiter" than our yellow sun. Rigel, a star in the constellation Sirius, is a white dwarf. Larger, cooler stars, called "red giants," emit more light in the red region, and are exemplified by Antares and Betelgeuse. Note that even a "cool" star still has a temperature of a million degrees or so.

While the sun does emit ultraviolet radiation, the majority of solar energy comes in the form of "light" and "heat," in the visible and infrared regions of the electromagnetic spectrum. As shown in Table 1, visible light spans the relatively narrow range of 0.4 to 0.9 µm (or 400 to 700 nm). Light is special to humans and many other animals due to the evolution of the eye, a sensory organ that detects this part of the solar spectrum. As noted earlier, our eyes even recognize parts of the visible light spectrum as the sensations of color. Thus 400 nm radiation is perceived by the eye as violet, and 600 nm radiation is perceived as red.

We are all familiar with the rainbow of colors - the range of different wavelengths that make up sunlight. The best way to visualize this concept - and the most common scientific demonstration - is the image of a glass prism splitting up white light into the colors. When raindrops act as prisms, we see a rainbow. Often, when the sun is bright, various transparent objects such as beveled edges of glass windows or glass pieces of a chandelier transmit light as a spectrum. This phenomenon occurs because different wavelengths of light (or different colors) travel through glass at different speeds, causing them to bend at different angles. Figure 3 shows the spectrum (violet, blue, green, yellow, orange, and red) going from the shortest wavelengths (highest frequency) to the longest wavelengths (lowest frequency). On either side of the visible spectrum are the ultraviolet (shorter wavelength than violet) and infrared (longer wavelength than red). These wavelengths are mostly absorbed by the glass and are, of course, outside the range of wavelengths that our vision can detect.

Figure 3: White light falling on a glass prism, dispersed into its constituent colors.
(from Lawrence Berkeley National Laboratory)

While the eye effectively perceives and distinguishes visible light, infrared (wavelengths longer than red) is perceived as heat when it is absorbed by the skin and converted into energy of the molecules of the skin. Infrared plays an important role in the temperature of the Earth and its atmosphere, and in turn, the climate of the Earth. We will discuss this role in more detail in the section pertaining to the interaction solar energy with the atmosphere.

We will now discuss how much energy is available in the different wavelength regions of the solar spectrum.

Energy Distribution in the Solar Spectrum

Electromagnetic energy can be discussed in terms of its energy distribution, or the spread of energy over a range of wavelengths. This distribution of energy is also known as the spectral distribution. The measure of radiation may be quantified in terms of the amount of energy falling per second (measured in Watts) per unit area (in square meters, m^2) in each band of 1 μm wavelength.

The sun provides a broad range of energy, primarily concentrated around the visible and infrared regions. This energy is an important feature of the background conditions that led to the evolution of our life forms on Earth, and continue to support this life. There is a small amount of high-energy radiation like x-rays in the sun's energy but these do not penetrate below the topmost layer of the atmosphere, and we do not consider them here.

In the ultraviolet region of the solar spectrum around 0.28 μm wavelength, there is less than 100 W/m^2 in a 1 μm band of radiation. In a 1 μm band around the red wavelength of 0.6 μm, however, there is over 2,000 W/m^2. From 0.75 μm or so, there is infrared radiation ranging from about 1,000 $W/m^2/\mu m$ at 0.8 μm to about 100 $W/m^2/\mu m$ at 2.2 μm. This relatively low level of energy persists far into the infrared region.

The spectral distribution (or range of energies) of the solar radiation that falls on top of the Earth's atmosphere is represented in Figure 4. As this spectral distribution is close to what the sun emits, we can say that this is the sun's emission spectrum. The x-axis (or horizontal axis) represents the range of wavelengths in the solar spectrum (measured in nanometers), while the y-axis (or vertical axis) represents the amount of power (Watts) in each micron-wide band of wavelength falling on each square meter just outside of the Earth's atmosphere (measured in units of $Watts/meter^2/\mu m$). This figure shows that most of the energy coming from the sun is in the visible region of the electromagnetic spectrum, making up what we call sunlight (white light).

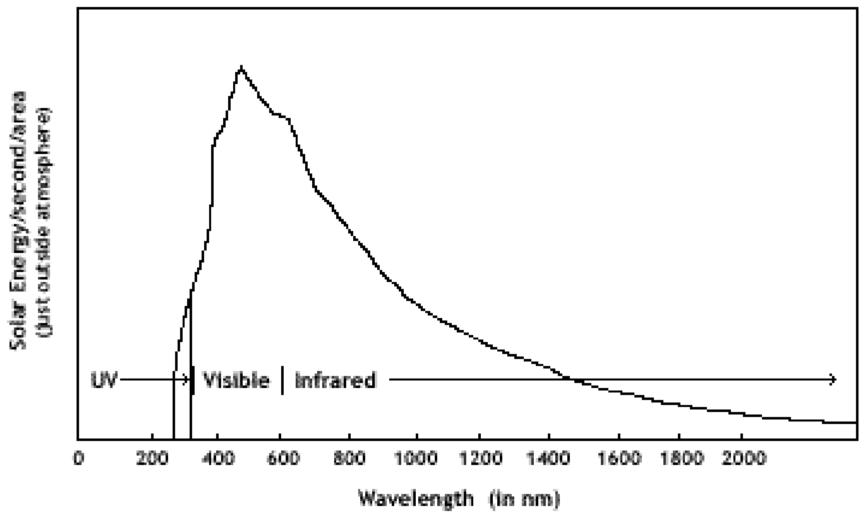

Figure 4: Solar spectral distribution entering the lower parts of the atmosphere.

Reflection and Absorption Spectra - Basic Science

When light falls on a surface, it can either be reflected, transmitted, absorbed, or varying degrees of all three. Different colored surfaces appear different to the eye because of differences in the way they reflect and absorb light. Stars are sources of radiation, giving off their own energy. Their color appears to us through the light they emit. So, a bluish star gives off more blue light than a yellow star like the sun. To see non-luminous objects, we need light from some other source to fall on them, and the reflected light reaches our eye. The colors of non-luminous objects are thus dependent on what wavelengths of energy they reflect and what wavelengths they absorb.

"White light" consists of the full spectrum of colors. If white light falls on a "perfectly" white surface, all of the light is reflected -causing all colors to reach the eye - and the reflecting surface is perceived as white. On the other hand, the perception of black is the absence of any color reaching the eye, meaning that all light is absorbed. In any case, the incident amount of energy (I), or the amount of energy falling on a particular surface, is equal to the sum of the amount reflected (r) and the amount absorbed (a).

The following figures show schematically what happens when white light falls on a perfectly white surface, on a perfectly black surface, and on a green surface. In each case, Part A of the figure represents what happens when a ray or beam of white light falls on the surface. Part B of all the diagrams shows the spectrum of incident radiation and the spectrum of reflected radiation, with the x-axis representing wavelength and the y-axis representing energy intensity. The third part of each diagram set, labeled C, shows what is known as the absorption spectrum, showing what wavelengths are absorbed. Note that in part C, while the x-axis still represents wavelength, the y-axis is now a measure of absorption and not energy. For simplicity we assume that all light not reflected is absorbed, although some might be transmitted. So what we label "absorption spectrum" below is actually an "absorption + transmission spectrum."

In the case of the white surface, almost all incident light is reflected. Thus the incident spectrum (I) and the reflected spectrum (r) are the same. Because none of the light is absorbed, the absorption spectrum (a) may be shown as a flat line close to zero.

FIGURES 5.1: WHITE SURFACE

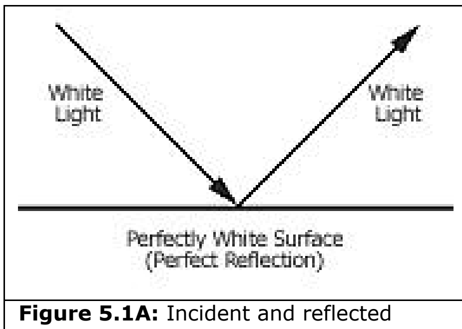

Figure 5.1A: Incident and reflected beams.

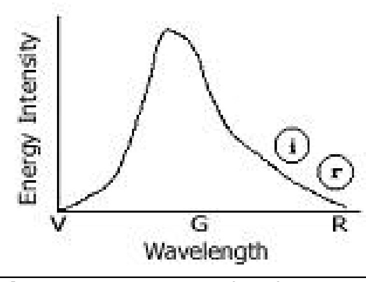

Figure 5.1B: Energy distribution in incident and reflected beams.

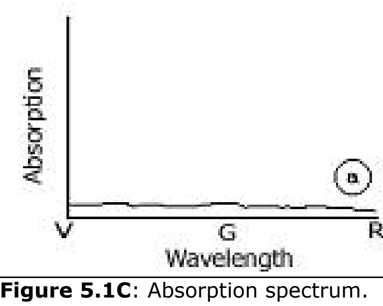

Figure 5.1C: Absorption spectrum.

When white light falls on a perfectly black surface, none of the incident light is reflected. Thus the same incident spectrum gives no reflected spectrum, represented by a flat line of almost zero energy. Because all incident light is absorbed, the absorption spectrum is the same as the incident spectrum.

FIGURES 5.2: BLACK SURFACE

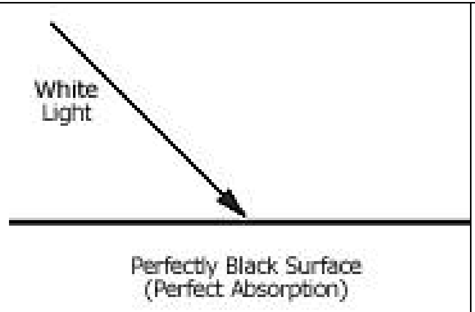

Figure 5.2A: Incident and reflected beams.

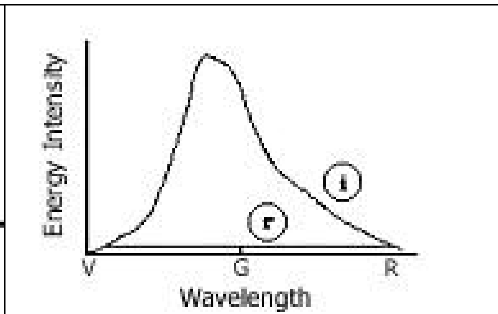

Figure 5.2B: Energy distribution in incident and reflected beams.

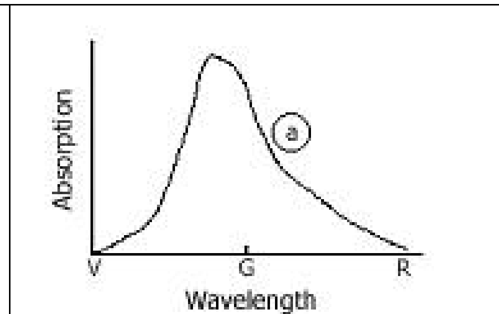

Figure 5.2C: Absorption spectrum.

In the example of a white light falling on a green surface, only green light is reflected. Once again using the same incident spectrum, the reflected spectrum this time centers around the wavelengths of green. The green surface also has a more complicated absorption spectrum: it absorbs both the violet-blue region and the red region as shown.

FIGURES 5.3: GREEN SURFACE

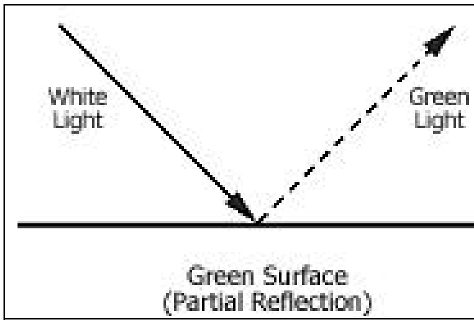

Figure 5.3A: Incident and reflected beams.

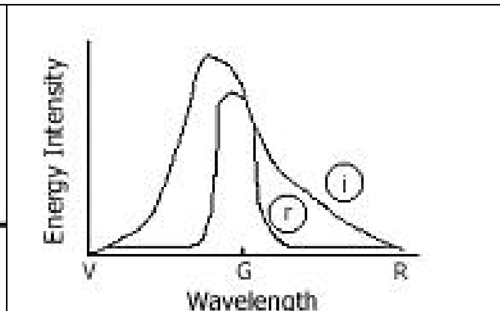

Figure 5.3B: Energy distribution in incident and reflected beams.

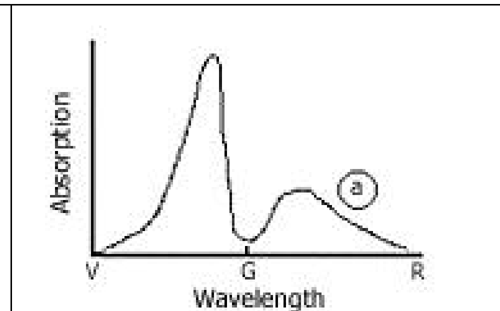

Figure 5.3C: Absorption spectrum.

Leaves appear green in sunlight (white light) because the chlorophyll molecules in the leaves preferentially absorb blue, violet, and red. Light from the green wavelengths is not absorbed; rather it is reflected and perceived by our eyes. The representation of this absorption is shown in the series of diagrams below labeled Figures 6.1-6.3.

Figure 6.1 shows the absorption spectrum of the most common forms of plant chlorophylls. It shows that chlorophyll of plants has high absorption at 400 nm (violet and blue), low at 500 to 600 nm (green and yellow), and high again at around 680 nm (red). The absorption is a measure of the "appetite" of the chlorophyll for the ranges of wavelengths to which it is exposed.

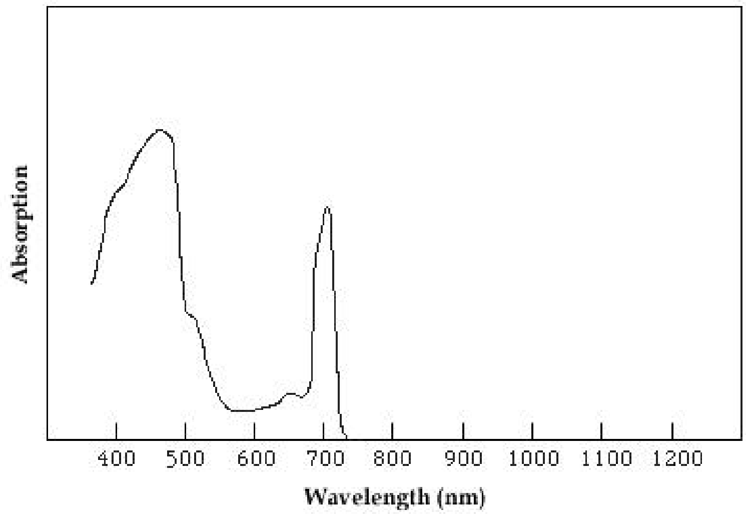

Figure 6.1: Absorption spectrum of chlorophyll.

Figure 6.2 shows this absorption spectrum (A) superimposed on a rough outline of the solar energy spectrum (B), which is an enlarged section of the solar spectrum shown in Figure 4. This figure demonstrates that when solar energy falls on leaves, the chlorophyll will absorb violet, blue, and red. The reflected spectrum therefore will have lost large portions of its energy around 400 nm and 800 nm, retaining energy mostly in the 500-600 nm (green) range, and in the infrared. The Ecological System describes photosynthesis in much greater detail.

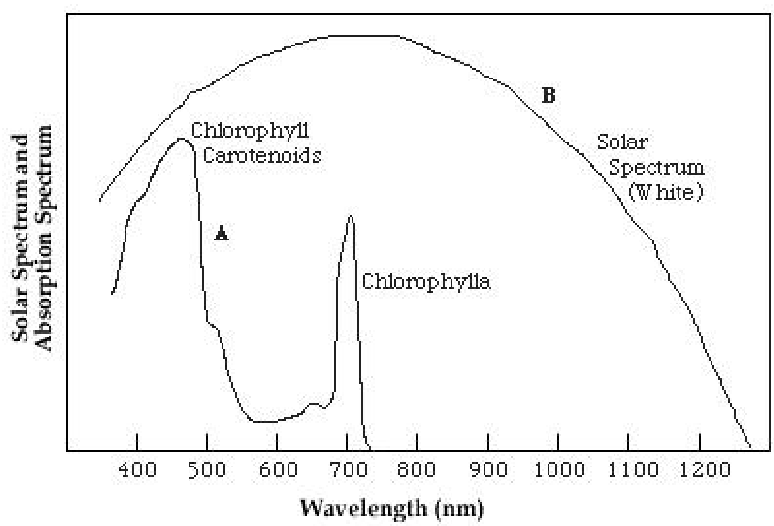

Figure 6.2: Solar spectrum of visible region juxtaposed with the absorption spectrum of chlorophyll.

Figure 6.3 shows the light that is left over after the absorption by chlorophyll occurs. This "reflected spectrum," then, actually represents the light (mostly green and yellow) that is reflected off the leaf. This is the detailed explanation of why leaves appear green in white light. The violet light absorbed by the chlorophyll is responsible for photosynthesis.

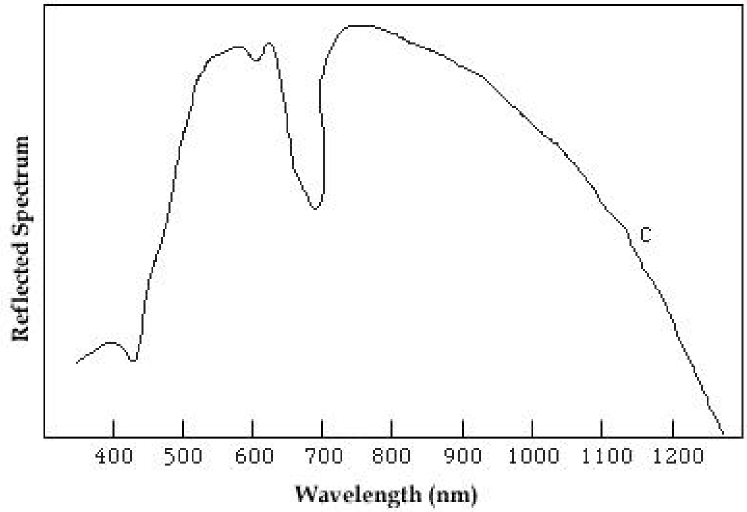

Figure 6.3: Reflected spectrum, or what is left of the solar spectrum after absorption by chlorophyll in a leaf. Our eyes register this as the leaf surface being green.

Earth & its Atmosphere

The Earth's mass exerts a gravitational force that holds to the Earth a large amount of gases, known as the atmosphere. In this section, we will look at the layers and general composition of the atmosphere and discuss its major roles in maintaining life on Earth. We will not discuss in detail how the atmosphere has evolved over the history of the Earth, nor how living systems on Earth affect the atmosphere. Note briefly, however, that James Lovelock, author of Gaia, proposes that the atmosphere owes its current composition to feedback from living systems. He remarks that life on Earth requires a particular atmospheric composition, and this composition is in turn maintained by the interaction between biological systems and the atmospheric system.

Layers of the Atmosphere

The atmosphere consists of five layers: the troposphere, the stratosphere, the mesosphere, the thermosphere, and the exosphere. The thickness of these layers is slightly different around the globe, and also varies according to temperature and season. In this discussion, we will focus primarily on the troposphere and the stratosphere because they are the most affected by anthropogenic (or man-made) pollutants.

The troposphere is the layer closest to the Earth's surface. It is a layer of air approximately 10 to 15 kilometers thick that is constantly in motion. The conditions in this layer determine practically all of the Earth's weather patterns. It derives its name from the Greek word "Tropos," meaning "turning" or "mixing." The constant motion in this layer is significant in discussing air quality because it results in the dispersion of pollutants. In one respect this dispersion is considered beneficial because it has the effect of diluting pollutants, which can reduce harmful impacts on a local level. On the other hand, this dispersion also results in the movement of air pollutants (and therefore air pollution problems) from areas of high pollution production to areas of lower production. For example, pollutants produced in an industrialized and heavily populated city often adversely impact smaller communities and ecosystems in a large surrounding area.

The stratosphere is the layer just above the troposphere. It is approximately 40 kilometers thick and is composed mostly of dry stable air. In contrast to the troposphere, pollutants in the stratosphere do not disperse, and tend to remain in the atmosphere for long periods of time.

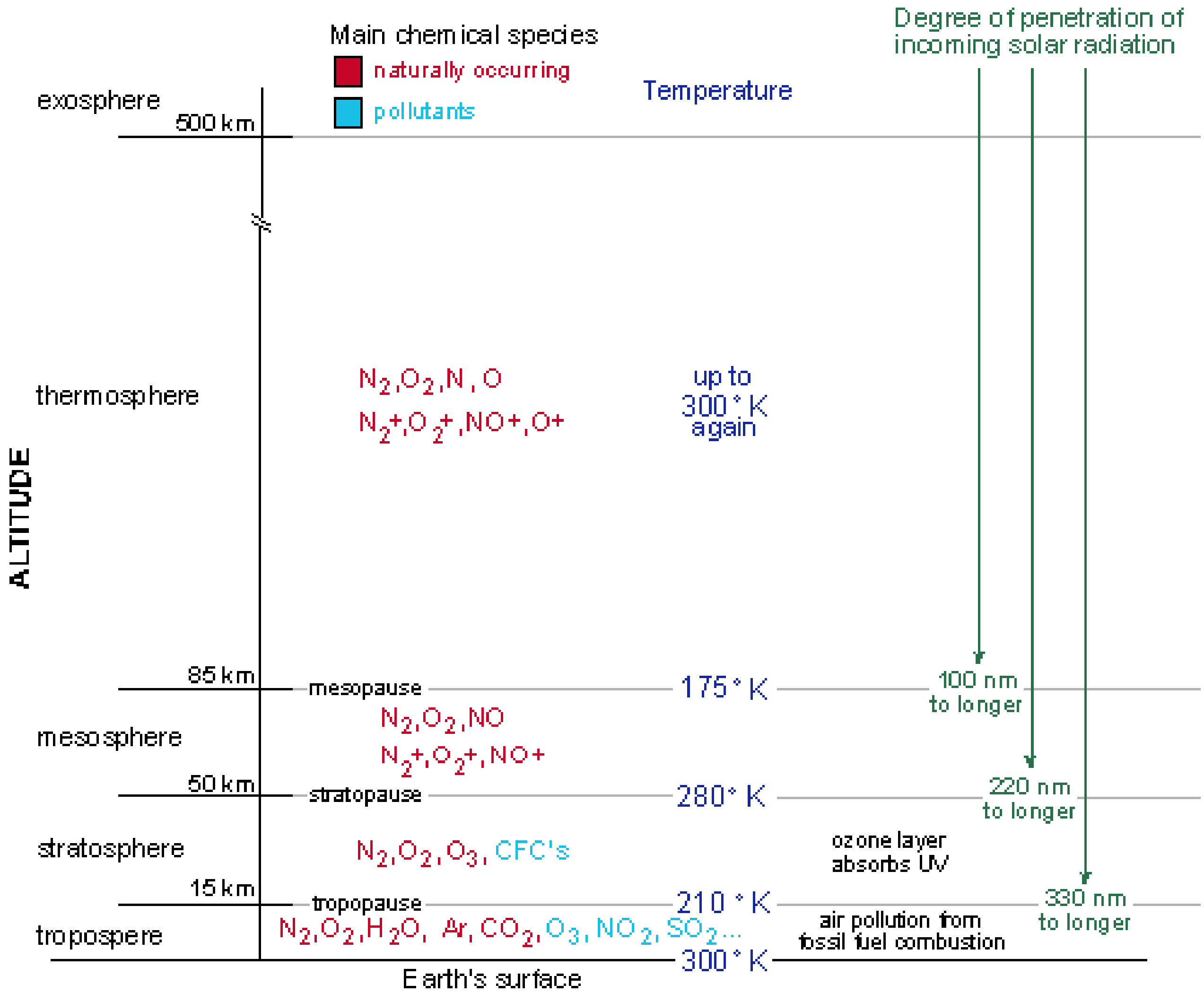

Figure 7: Layers of the Earth's atmosphere.
(adapted from G.W. Vantoon and S.J. Duffy, Environmental Chemistry: A Global Perspective, Oxford University Press, 2000.)

As electromagnetic radiation travels through the atmosphere, shorter wavelengths are absorbed by the molecules in the first few miles. This high frequency radiation is capable of stripping the electrons from the molecules and dissociating the O_2 and N_2 molecules into O and N atoms, and ions or charged units such as O_2+, N_2+ (O_2 and N_2 molecules with one electron missing), etc. Thus the upper layers of the atmosphere are also called the ionosphere because they contain ions (or charged atoms and molecules). Only radiation of wavelength 220 nm or longer penetrates deeper into the atmosphere, reaching the stratosphere.

A stream of charged particles from the sun and the galaxy in general also falls on the upper layers of the atmosphere. Because they are charged, they are affected by the Earth's magnetic field--and depending upon their charge (+ or -) spiral toward the North or South pole. These concentrated streams of particles (often referred to as "cosmic rays") falling on the poles are visible as the Northern and Southern Lights (Auroral Lights).

Figure 2, Table 1, and Figure 4 all show that the spectral region from about 10 nm to about 350 nm is the ultraviolet region. The absorption spectrum of the ozone molecule is from 240 to 300 nm, while the O_2 molecule absorbs wavelengths shorter than 175 nm (splitting into O atoms). This absorption of the O_3 and O_2 molecules is the basis of the ozone layer (more later).

Chemical Composition of the Atmosphere

The Earth's atmosphere is composed primarily of nitrogen and oxygen, as well as some argon. There are also several other trace gases, meaning they occur in very small amounts. The proportion of molecules that naturally occur in the troposphere is described in Table 2. It is important to note the concentrations of these chemical compounds compared to the anthropogenically generated chemicals that may enter the atmosphere.

The major constituents are oxygen (O_2) and nitrogen (N_2). Other components such as argon, CO_2, NO, and O_3 are produced in minute quantities in natural processes. However, industrial and other technological human activities (such as automobile traffic) have begun to increase the amounts of materials such as CO_2 by amounts that are beginning to make a difference in the balance of circulation and radiation absorption in the troposphere. Effects of these changes range from local atmospheric problems, like smog, to problems of much greater scale, such as global climate change (more later).

Chlorofluorocarbons (CF_2Cl_2, $CFCl_3$) are a family of chemicals that do not occur in nature, but were produced in large quantities in the last century. These chemically inert compounds rise into the stratosphere and cause disruptions in the ozone layer (more later).

Numerous other gases circulate particularly in the troposphere in small quantities. The rare gases Argon (Ar), Neon (Ne), and Krypton (Kr) slowly drift up released from various processes on the ground, and remain non-reactive. Water vapor (H_2O), carbon dioxide (CO_2) and methane (CH_4) also arise from natural processes.

Water is the most highly variable gas in the atmosphere. The water fraction in the atmosphere (measured by the relative humidity) varies from place to place and day to day.

The water cycle described in the Materials System unit is, of course, vital to life on Earth, as is a certain level of C O_2. H_2O and C O_2 are essential molecules for photosynthesis. H_2O and CO_2 are also central in moderating the temperature of the atmosphere as the Earth rotates (more later).

CO_2 is produced in natural processes of decay and natural combustion processes such as forest fires and volcanoes.

Methane arises from natural processes such as cows and paddy fields. It is also produced in numerous underground processes of decay in the soil in the absence of oxygen, especially in marshes. Another source of the release of methane into the atmosphere is during the extraction and transportation of natural gas.

Carbon monoxide, oxides of nitrogen, NO, NO_2, and more complex nitrogen compounds are formed as a byproduct of the operation of the internal combustion engine and other fossil fuel-based technologies. Thus in countries with high levels of transportation, these gases also exist in local regions of the atmosphere. Oxides of sulfur are also released in coal burning (more later).

The troposphere is therefore a highly varying mixture of gases. Note that compared to the amounts of oxygen and nitrogen, the other gases are in small quantities measured in units of parts per million (or ppm) meaning one molecule of the gas in every million molecules of air (approximately 780,000 N_2 and 21,000 O_2). These small ppm-level imbalances in the composition of the atmosphere are enough to cause disruption in local and global atmospheric conditions and affect temperature and weather patterns.

Constituent	Concentration
Nitrogen	78.08%
Oxygen	20.95%
Argon	0.93%
Carbon Dioxide	355 ppm
Neon	18 ppm
Helium	5.2 ppm
Methane	1.8 ppm
Krypton	1.1 ppm
Nitrous Oxide	0.3 ppm
Hydrogen	0.5 ppm
Ozone	0.01 ppm

Table 2: 1990 Composition of Clean, Dry Air
(fraction by volume).

Solar Radiation in the Atmosphere

The atmosphere may seem to be completely transparent to solar radiation, but in fact there are dynamic interactions occurring constantly that result in a complex and delicately balanced system crucial to the continuation of present life forms on Earth. In this section we will discuss how solar radiation is absorbed and reflected by the atmosphere and the Earth -- and two resulting phenomena that are crucial to the maintenance of life on Earth:

1. The atmosphere acts as a filter, absorbing and reflecting portions of the electromagnetic spectrum, such as the ultraviolet region, that are harmful to humans and other life forms.

2. The atmosphere provides a natural "greenhouse effect," maintaining the temperatures and climates in which life forms on Earth have evolved to survive.

The atmosphere controls the amount of solar radiation reaching the surface of the earth, and regulates the amount of radiation from the Earth escaping into space. Even seemingly slight changes in the concentrations of certain gases could upset the balance of reactions and be detrimental to life as we know it. We will now explain these two exchanges in detail, and later discuss their relevance to two major environmental problems: global climate change and stratospheric ozone depletion.

To demonstrate how the atmosphere affects incoming solar radiation, Figure 8 shows the solar radiation spectrum first at the top of the atmosphere (A, in red), and again at sea level (B, in blue). The absorption of the molecules shown in Figure 8 is discussed in some detail because it is critical to maintaining some of the most important conditions for our viability on Earth. Note that the solar spectrum shown here is the same as a part of Figure 4, enlarged to show the details of absorption.

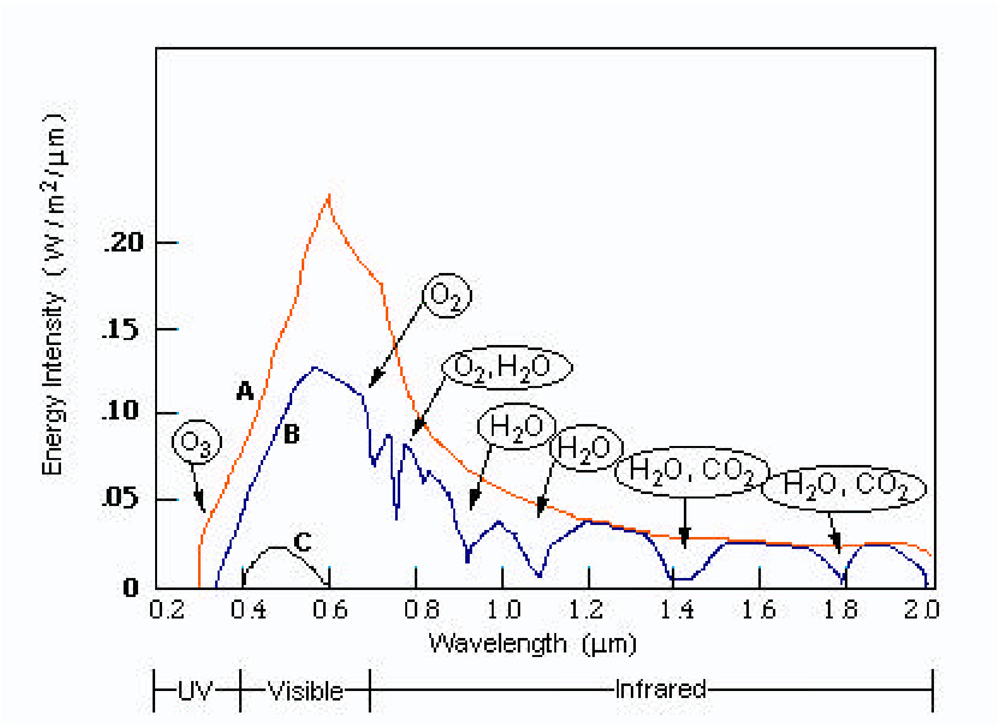

Figure 8: Solar spectrum (A) above the atmosphere and (B) near the Earth's surface, with some of the radiation having been absorbed by molecules in the atmosphere. Also depicted is a curve of the spectrum detectable by the eye (C).

This figure shows that ozone (O_3) absorbs ultraviolet. O_2 absorbs ultraviolet as well as some visible and infrared. The ultraviolet absorption properties of O_3 and O_2 are central to the protective ozone layer described later. Water vapor (H_2O) absorbs highly in the range of 0.4 and 0.9 µm and again above 1.2 µm and also in the microwave region. The absorption property of H_2O in the microwave region is, of course, the basis for the efficient cooking of foods by microwave ovens. CO_2 has high absorption around 1.4 µm and above.

When molecules absorb energy, the absorbed energy may go into causing a chemical change (as in cooking food in a microwave oven), or it may be re-emitted. Often molecules re-emit energy at wavelengths longer than that at which it was absorbed. Thus when molecules such as H_2O and CO_2 absorb visible or infrared light, they often re-emit it as longer wavelength infrared. This has great importance in our climate as described later.

The small black curve labeled C in Figure 8 approximates the sensitivity spectrum of our vision, or which wavelengths the eye can detect, with our maximum sensitivity by the green and yellow. This is why yellow light is used for markings on the roads and as the warning light color in traffic lights.

Atmospheric Environmental Concerns

Air pollution problems occur due to the presence and movement of pollutants within and among the layers within the atmosphere. The location of the pollutants in a certain layer is an important factor in determining what type of air pollution problem may occur. For the most part, the polluting molecules are heavier than air and circulate in the troposphere. A general description of these are given earlier. The different species of molecules remain in the troposphere for different amounts of time depending upon their amount, reactivity, and local weather patterns. It is the non-reactivity of chlorofluorocarbons that result in their drifting through the troposphere and finding their way tot he stratosphere. Most of the CFC's do remain in the upper part of the troposphere due to their weight. However very little ultraviolet reaches here because of the stratospheric ozone layer. Recall that their ability to disrupt the ozone layer occurs due to ultraviolet knocking off a chlorine atom. So this does not happen in the troposphere. Otherwise we might have other problems stemming from free highly reactive chlorine in the troposphere!

The fastest transport of gases in the atmosphere occurs in the troposphere. This is the region where the circulation patterns leading to the daily weather and eventually the climate conditions occurs. The water cycle (described in the Materials System) occurs between the earth (particularly oceans and other bodies of water) and the lower half of the troposphere. The troposphere extends to about 9.5 miles (15 km) from the Earth's surface. When pilots announce the altitude of an airplane flight and you are above the clouds, it is usually at 30000 - 35000 feet which is about 5 - 6 miles. So the cloud activity is generally in the lowest part of the atmosphere. Even with the faster circulation in the troposphere, on the average, a water molecule spends about 9 days in the atmosphere once it gets released from the water bodies of the earth. This is called the residence time of the molecule in the water. Molecules like CFC's on the other hand have residence times varying from 60 years to hundreds of years!

Some of the effects of pollutants in the atmosphere are global, some regional, and some local, depending on the layer at which they primarily circulate, which in turn depends on how heavy the molecule is, its reactivity , and what the circulation patterns are.

Climate change, indicated by the so-called greenhouse gases and stratospheric ozone depletion are global in nature. Acid precipitation (or acid rain) due to release of oxides of sulfur and nitrogen from fossil fuel combustion is regional, and affects areas up to hundreds of miles from the sources. Tropospheric (or ground-level) ozone concentrations, air pollution from CO, NO_2, and SO_2, and heat island effects arising from the interaction of pollution with sunlight or with local circulation patterns set up by buildings are local in nature and vary daily. These effects are now described in more detail.

Stratospheric Ozone Layer & Ozone Depletion

Ultraviolet Filtration and the Ozone Layer

Let us look in detail at the first protective mechanism afforded by the fact that O_3 and O_2 both absorb ultraviolet but at slightly different wavelengths. O_3 absorbs in a region from 240 - 280 nm and O_2 absorbs wavelengths shorter than 175 nm. The energy absorbed in both cases is used to effect chemical change rather than re-emitted.

The UV radiation absorbed by O_2 in the stratosphere actually splits the O_2 into oxygen atoms. Each of these oxygen atoms combine with other oxygen atoms to form O_2 or with O_2 to form O_3. O_3 absorbs UV at the higher wavelengths (240-280 nm) to split into O and O_2. The O released by O_3 may recombine with an O to form O_2 or with water to form 2OH radicals. These changes may be outlined in terms of the following equations:

1.	O_2 + UV radiation (< 175 nm) → O + O
2.	O + O_2 → O_3 *or* O + O → O_2
3.	O_3 + UV radiation (240-280 nm) → O* + O_2 gas

4.	$O^* + O \rightarrow O_2$ *or* $O^* + H_2O$ 2OH
	and so on...

This cycle repeats and, over millions of years, has reached an equilibrium state. The net result of the above reactions is that O_2 and O_3 are constantly changing into each other, and each cycle takes up energy in the form of ultraviolet radiation, resulting in a large reduction of the amount of ultraviolet radiation reaching the troposphere. These reactions also result in there being a higher concentration of ozone gas in the lower region of the stratosphere with a maximum of O_3 occurring between 20 and 26 km above the Earth's surface. This area is called the "ozone layer."

In general, ultraviolet radiation of the smaller wavelength damages the skin, and can initiate the process of skin cancer. The stratospheric ozone layer forms a protective shield protecting us from receiving large amounts of UV. Note however that some ultraviolet does get through and is responsible for sunburn, and skin cancer with excessive exposure.

The ultraviolet A absorbed by the skin can actually damage our DNA. Most of us have repair genes that can repair this damage, however when we are exposed to large amounts of UV, the repair is not enough to keep up with the damage and this damage can result in skin cancer. People who can not produce skin pigment (referred to as "albino") have a genetic condition known as xeroderma pigmentosum, which is accompanied by a lack of the UV repair gene. These people are therefore several hundred times as likely as the average person to contract skin cancer.

Ozone-Depleting Substances

Humans have introduced many compounds into the atmosphere that are capable of disrupting the cycle of creation and destruction of ozone molecules in the stratosphere. A family of compounds known as chlorofluorocarbons (CFC's) have had the most significant effect on the ozone layer by far. This discussion will focus primarily on CFC's, although the basic process of ozone depletion is very similar for any of the ozone-depleting substances (ODS).

CFC's have varying compositions, but all of them contain different proportions of three elements: carbon (C), Chlorine (Cl) and fluorine (F). Two of the CFC's that were in common use are: CFC-11 ($CFCl_3$) and CFC-12 (CF_2Cl_2)

CFC's were produced and used extensively as refrigerants starting in the early 1930's. They were discovered by a scientist named Medgley who was searching for a more ideal cooling compound to replace the unsafe chemicals that were being used at that time, including ammonia and sulfur dioxide. Ammonia was most widely used, but was undesirable because it is a strong eye and respiratory irritant.

Chlorofluorocarbons were seen then as the ideal compounds because they are extremely non-reactive, and were therefore thought to be harmless. They are chemical inert, non-toxic, and insoluble in water. For close to fifty years, they were hailed as miracle substances, and were used extensively in aerosols, refrigerants, and foams.

What we did not know then was that because of their non-reactive nature, CFC's are able to rise undisturbed into the atmosphere. They are not destroyed by reactions or removed by precipitation in the tropospheric layer of the atmosphere, and migrate over several years, eventually reaching as high as the stratosphere.

Disruption of Ozone Cycle

When CFC's migrate high enough and are hit by enough ultraviolet radiation, they are broken down and release chlorine atoms. The chlorine atoms react with O_3 gas and the following chain of reactions results:

$Cl + O_3 \rightarrow ClO + O_2$

$ClO + O \rightarrow Cl + O_2$

These reactions make ozone molecules unavailable for the vital reactions that absorb incoming ultraviolet, and are the main source of ozone depletion. One chlorine atom can destroy over 100,000 molecules of ozone, and the result of this disruption is a markedly lower than expected concentration of stratospheric ozone at various points around the world.

Results

The possibility of ozone depletion in the stratosphere was predicted in the 1970s by two scientists named Roland and Molina. They based their prediction on the action of CFC's on the atmosphere. Although stratospheric ozone depletion is often referred to as the "ozone hole," that term is misleading. What we call a hole is actually a sharp reduction in expected ozone concentrations. Scientists have defined an ozone hole as an area having less than 220 dobson units (DU) of ozone in the overhead column (i.e., between the ground and space).

Lower ozone concentration means that less incoming ultraviolet radiation is absorbed by the reactions described earlier, and more reaches the troposphere and the Earth's surface. Humans and other forms of life are exposed to higher levels of ultraviolet, which can cause more damage to skin cells and sensitive tissues of the eye than they are capable of repairing.

Ozone depletion, or the concentration of stratospheric ozone, varies seasonally and latitudinally. There tends to be more ozone depletion in the winter with more depletion at the polar regions. The science behind this is somewhat uncertain but is related to the reaction surfaces that are caused by cold cloud formations near the poles.

Possible impacts from ozone depletion are related to the effects on ecosystems by ultraviolet radiation. The exact cause and effect relationship for many of these impacts is uncertain. The impacts are:

- Malignant skin cancer
- Non-malignant skin lesions
- Lower crop productivity
- Cataracts
- Ecosystem abnormalities

Policy Efforts

In 1987, the first substantial international environmental treaty was passed. It is known as the Montreal Protocol and includes agreements to reduce the worldwide production of CFCs. The Protocol was precedent-setting in that it included funds to the developing countries to compensate for the higher costs of using alternate technologies.

The Montreal Protocol has been effective in lowering the production of CFCs in the U.S., although many developing countries have a longer time period for compliance. However, the CFC molecule is so stable (lasting 1700 years or more in the atmosphere) that previously produced CFC's will be entering the stratosphere continuously and we will feel their impacts for many years to come.

Several substitutes for CFC's are being developed. The desirable property of CFC -- its chemical inertness -- is also the reason it is able to reach the stratosphere. To engineer a substitute, one must design a compound that has the desirable properties but will not contribute to stratospheric ozone depletion. The new compounds being considered have less chlorine and fluorine. The most common replacements are HCFCs in which one chlorine is replaced by hydrogen, or HFCs in which chlorine is altogether replaced by hydrogen. Examples are $CHClF_2$ and CH_2F_2. The lowered chlorine compounds are also banned in the U.S. after 2000 by the Clean Air Act.

The Greenhouse Effect & Global Climate Change

Solar Radiation Absorption, Balance, and the Natural Greenhouse Effect

The atmosphere plays a role similar to that of a greenhouse. When solar radiation falls on the atmosphere, part of it is transmitted and part of it is immediately reflected back into space. As the transmitted radiation travels toward the Earth's surface, different regions of the spectrum are absorbed by the molecules of the atmosphere. Energy that is not reflected or absorbed by the atmosphere falls on the surface of the Earth. In turn, the energy that falls on the surface of the Earth is either reflected back into the atmosphere or absorbed by the surface of the Earth. For every 100 units of solar radiation falling on the Earth and its atmosphere, 25 units are reflected by the atmosphere, and 25 units are absorbed by the atmosphere. The remaining 50 units fall on the surface of the Earth. Of these 50 units, 5 units are reflected by the surface of the Earth, and 45 units are absorbed. So altogether, approximately 30% of the incident energy is reflected by the atmosphere and the surface of the earth. This portion is known as the "albedo." Thus, the atmosphere absorbs approximately 25% of the radiation, and the earth's surface absorbs 45%.

Some of the energy absorbed by the Earth is used to evaporate water, driving the water cycle. The Earth then reradiates some of the remaining energy. This re-radiated energy contains more infrared than the original incoming radiation. So now the total amount of radiation present in the atmosphere, on the whole, contains longer in wavelength ranges than the original solar radiation that came to the Earth. Certain gases in the atmosphere (known as greenhouse gases—see Appendix I) do not allow this longer wavelength radiation to pass through as easily as the shorter-wavelengths that entered. These gases absorb, retain, and re-radiate the infrared, keeping a "warm blanket" around the Earth that prevents sudden cooling and heating effects each time the face of the Earth rotates away from or towards the sun. The two components of the atmosphere primarily responsible for the natural greenhouse effect are H_2O and CO_2.This moderating effect - one that is a net result of visible radiation being transformed increasingly into infrared and shorter infrared to longer is called the "natural greenhouse effect."

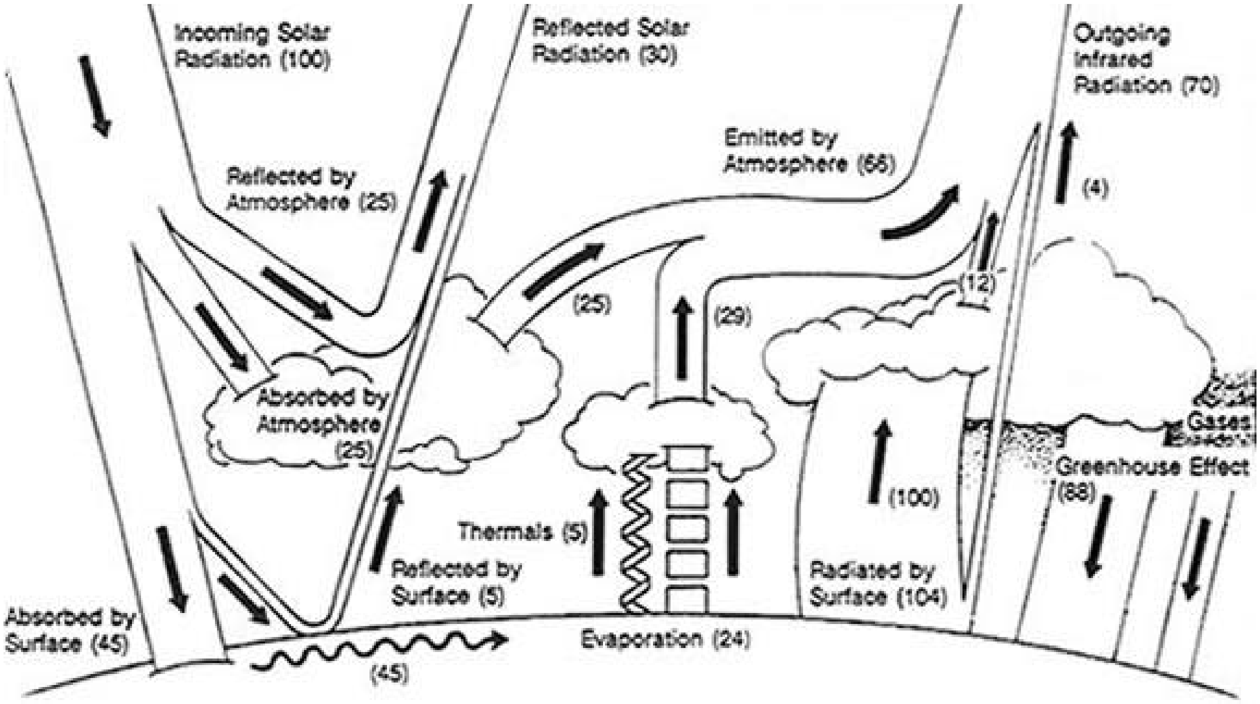

Figure 9: Solar energy balance.
[© Steve Schneider (1989) "The Greenhouse Effect: Science and Policy." Science 243: 771-81.]

Most light energy that reaches the Earth (approximately 90%) is absorbed by the surface of the Earth and other objects on it. Energy is then converted to long-wave radiation and re-emitted, as described in the example of the greenhouse above.

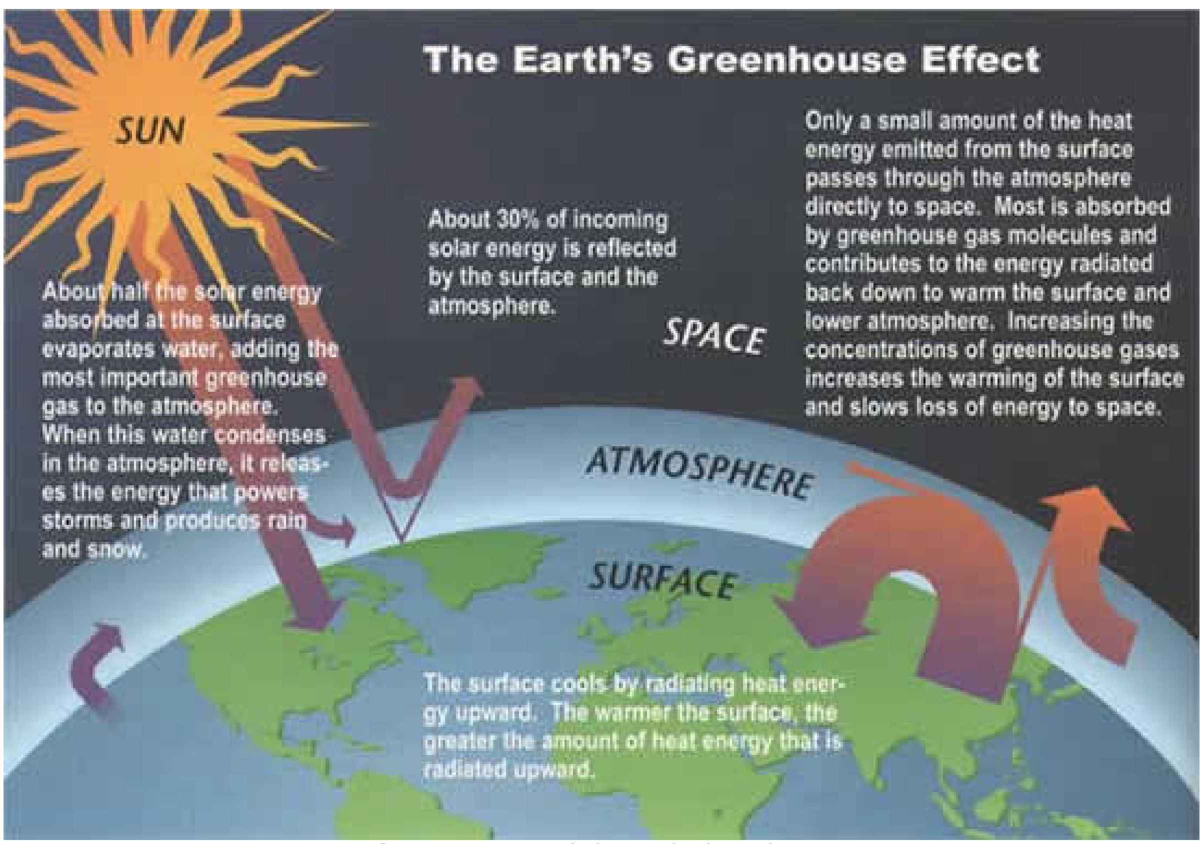

Figure 10: Energy balance of solar radiation.
(from Climate Change Impacts on the United States Cambridge University Press: 2000.)

The phenomenon we described above is known as the natural greenhouse effect, and is responsible for keeping the temperature of the Earth a full 33° C warmer than it would be otherwise. It creates a climate in which humans and other life forms can live under relatively hospitable conditions. However, human activities are causing a rapid increase in the concentrations of greenhouse gases, and we are now facing an "enhanced" greenhouse effect. The result of the enhanced greenhouse effect is an increase in the global average surface temperature of the Earth -- and possible changes in climate on a global scale.

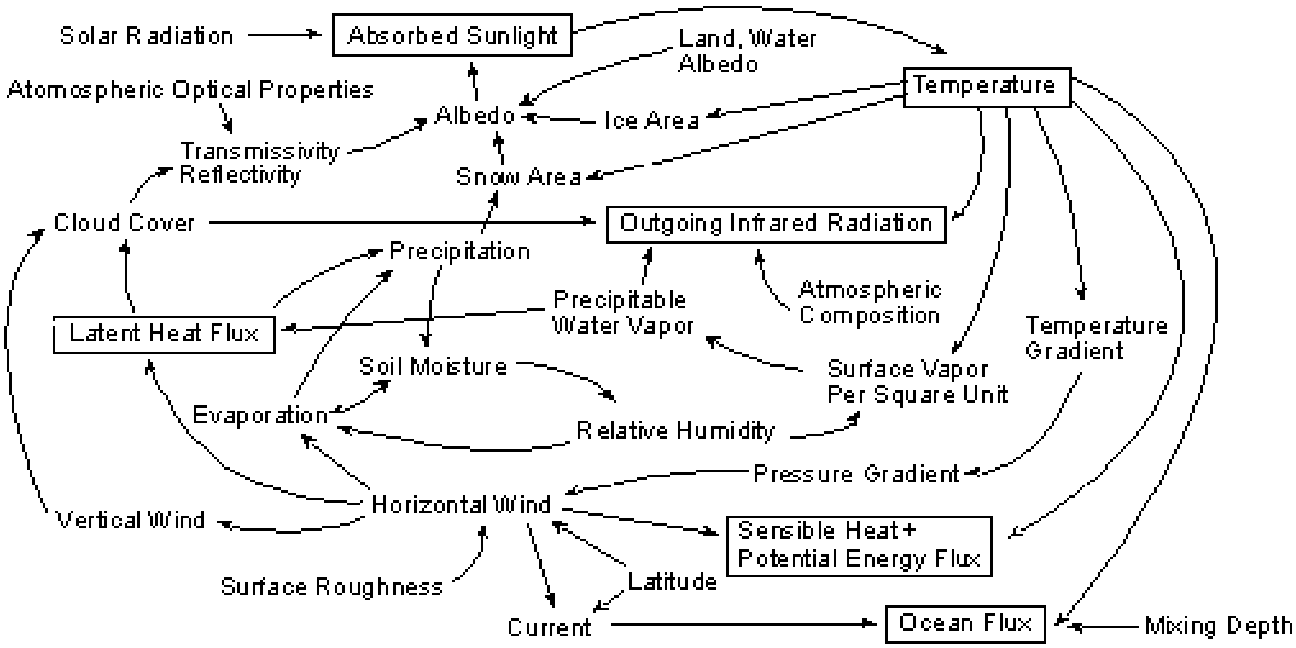

Figure 11: Scheme of greenhouse effect.
(From John R. Herman and Richard A. Goldberg:
Sun, Weather, and Climate. Washington D.C.: NASA, 1978.)

Global Climate Change

We noted earlier that even slight increases in the concentrations of greenhouse gases in the atmosphere result in more heat being trapped. In this section, we will summarize the scientific evidence that the increase in concentration of greenhouse gases impacts global climate conditions. We will also discuss the human activities that are causing the increase, and the policies that have been put in place to slow or reduce the effects of global climate change.

Recall from the previous section that there is a natural greenhouse effect that is necessary to maintain temperatures warm enough to sustain current ecosystems. This "temperature bath" occurs due to the absorption of short-wave (visible) solar radiation by surfaces on the Earth, and the subsequent transformation of that radiation into longer-wave infrared. Infrared is then absorbed and "trapped" by greenhouse gases, causing the troposphere to maintain a significantly warmer temperature than it would without this effect. Natural sources of greenhouse gases are part of a balanced chemical cycle that has been relatively steady during the time of human evolution to the present form.

As current ecosystems evolved over long time periods to acclimate to the environmental temperature, a permanent increase of even 1° on the average can be very disruptive, especially when this change occurs too quickly for the system to co-evolve.

Geologic evidence has been used to understand the correlation between the amount of CO_2 in the atmosphere and global temperature and climate. For example, it is believed that when life began around 4 billion years ago, the sun was about 30% fainter than it is today. However, much higher levels of CO_2 in the air (about 1000 times what they are today) made for enough warmth on the surface of the earth so at least some regions were above the freezing point of water, and began to provide conditions necessary for life to emerge. Analysis of CO_2 in the frozen layers of ice in Antarctica provides evidence that over the past 160,000 years, climatic change and levels of carbon dioxide are closely related.

The greenhouse effect can become a "problem" when the amount of heat-absorbing gases in the atmosphere rapidly rises far above the levels at which they have been historically present. Since the Industrial Revolution, there has been a high rate of increase in the concentration of greenhouse gases, due in large part to the combustion of fossil fuels and the destruction of large plant systems such as tropical forests. Carbon dioxide concentrations, for example, have risen by 30% since the late 1800's. Furthermore, scientists predict that CO_2 concentration will continue to rise, likely reaching 2 to 3 times its pre-industrial level by 2100.

The hypothesis that the known increase in greenhouse gas concentrations have led and will continue to lead to changes in the Earth's climate has been hotly debated in the past decade. However, a vast majority of scientists are now in agreement that evidence is sufficiently strong to prove the relationship. They are now mostly concerned with how to predict the impacts and scale of climate change, and how society can adapt to and minimize the harmful effects of these changes (see Appendix II).

Reliable temperature records only exist of the last century or so, and scientists use paleohydrologic studies to extract longer-term records. These data show that global average surface temperature can vary greatly over short periods of time. For example, there was an apparent temporary cooling during the 1940's, 50's, and 60's. However, the past century has seen an overall increase in temperature by 1° F (or 0.6° C), with about half of that increase occurring since the late 1970's. Seventeen of the eighteen warmest years of the 20th century occurred between 1980 and 2000.

These studies have also shown a positive correlation between greenhouse gas concentration and temperature, as shown by Figures 12.1 and 12.2. Notice on each graph that the blue line indicates readings taken from historical records, tree rings, corals, and air trapped in Antarctic ice, while the shift to a purple line indicates temperatures and CO_2 concentrations directly measured and recorded.

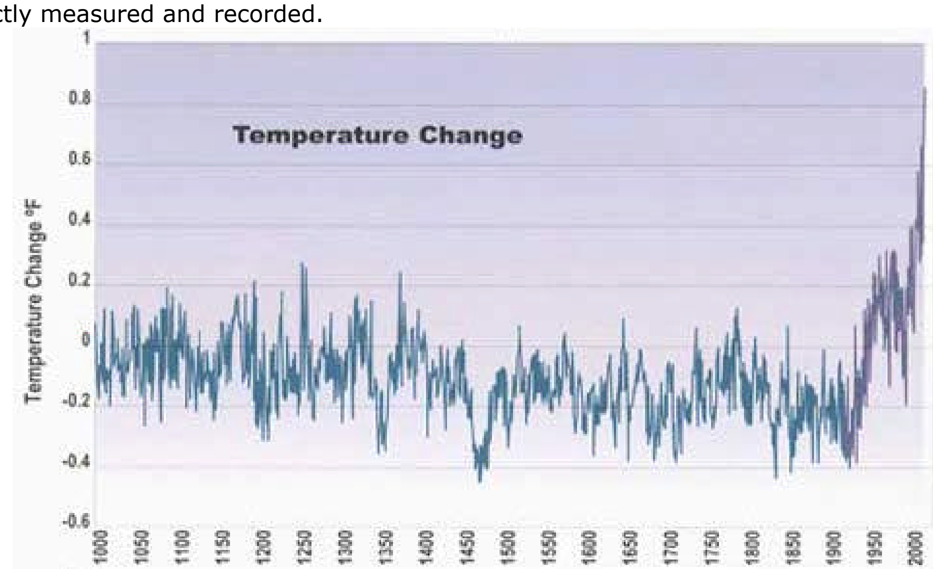

Figure 12.1: Graph of temperature change over past 1000 years.
(from Climate Change Impacts on the United States Cambridge University Press: 2000.)

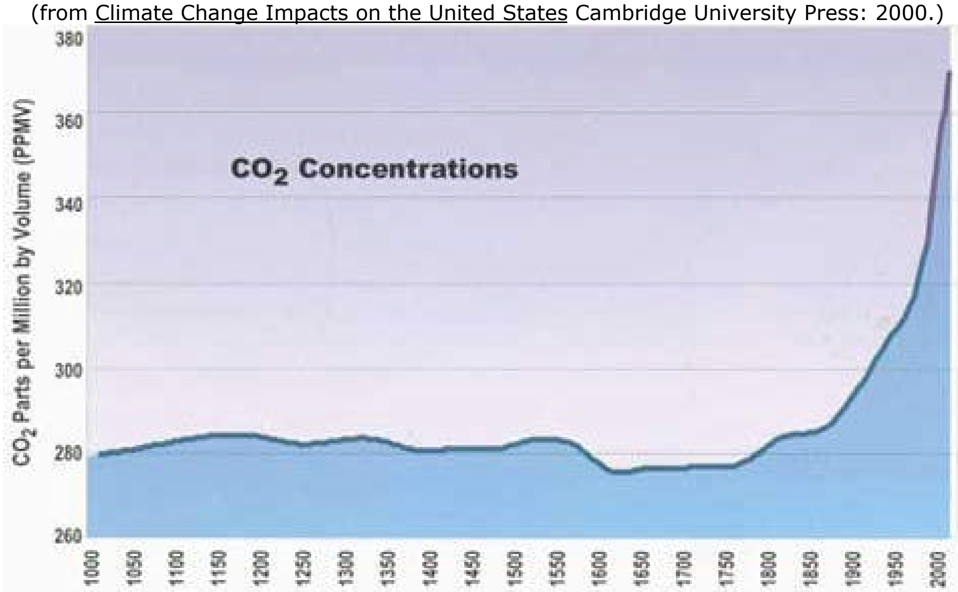

Figure 12.2: Atmospheric CO2 concentration over past 1000 years.
(from Climate Change Impacts on the United States Cambridge University Press: 2000.)

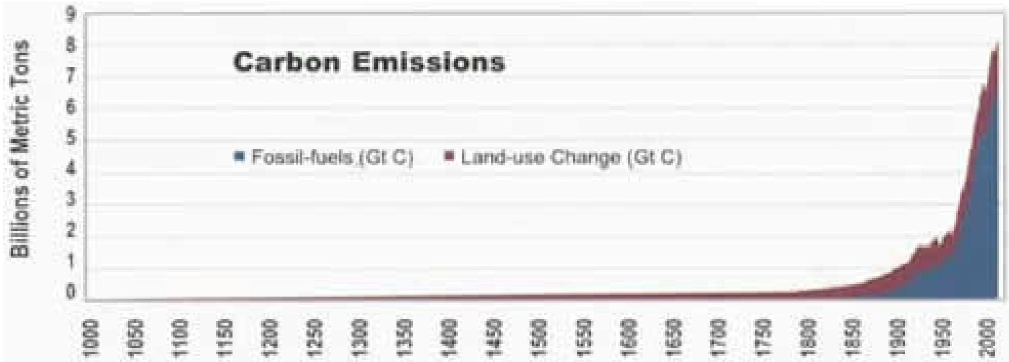

Figure 12.3: Carbon emissions over past 1000 years.
(from Climate Change Impacts on the United States Cambridge University Press: 2000.)

Policy

Since fossil fuel combustion is one of the primary sources of greenhouse gases, fuel use is indicative of those countries that have contributed most to global climate change. The US leads the world in the gross amount of carbon emissions from fossil fuels, followed by China. Overall, developing countries contribute a very small percentage as compared to industrialized nations. In speaking of CO_2 emissions, we normally speak in terms of carbon emitted, rather than CO_2 emitted. The US is also the leader in terms of the amount of carbon dioxide emitted per person, while China is the leader in terms of carbon emitted per dollar GNP.

While developed countries produce the vast majority of the carbon emissions from fossil fuel use, they often use more environmentally efficient technology. As highly-populated developing countries are becoming more industrialized, we risk a further leap in greenhouse gas concentrations due to the use of outdated (cheaper) technology.

There have been many international meetings regarding climate change since 1979 and they continue today. The most recent meeting that resulted in international agreement was the Kyoto conference in 1997. The debate there was between industrialized and the developing nations. The points made by each are as follows:

- Industrialized countries claim that most of the population growth is occurring in the developing countries, and most of the negative effects of climate change will affect those countries. Therefore, the developing world should be active participants in curtails on greenhouse gas emissions.

- Developing countries claim that industrialized countries caused these problems as they achieved their socioeconomic status. As such, the industrialized countries should be solely responsible for minimizing emissions etc., since emission limits would slow development in the developing countries.

The following preliminary agreement was reached as part of the Kyoto Treaty:

- 38 industrialized countries agreed to lower their greenhouse gas emissions by a combined 5.2% of 1990 levels by 2008. Of this, the US agreed to 7%, Japan to 7%, and Europe to 8%.

- There were no emissions reductions for the developing countries.

- An analysis of these agreed reductions would mean that due to population growth, the USA would have to reduce its carbon emissions by 33% of what it *would have been* in 2008. However, because the US lobbied for the inclusion of the effects of carbon sinks (or the "recapturing" of carbon by new forest growth, etc.) the reduction of actual *emissions* of greenhouse gases by 2008 only amounts to 2-3% less what the emissions were in 1990.

- In spite of the efforts of industrialized nations to reduce greenhouse gas emissions, it is understood that the overall atmospheric concentration of greenhouse gases would still increase due to the impacts of the developing world.

In order for this initial agreement to be considered binding, at least 55 countries must have the Treaty officially ratified and put in place by their individual governments. Furthermore, the 55 countries that ratify the Treaty must produce at least 55% of the world's greenhouse gas emissions. Otherwise, the Kyoto Treaty is not binding to the countries that signed it, and results will not be achieved.

Although the US signed the Kyoto Treaty within a year of its proposal, it has yet to be put before the Senate, where it would need a 2/3 vote to ratified. Shortly after taking office in 2001, President Bush suggested that the US may be withdrawing from the Kyoto treaty. His administration points to the "energy crisis" in California, possible threats to the economy, and lack of regulation of emissions in developing nations as the primary reasons for pulling out.

A more detailed explanation of the Kyoto Protocol can be found at http://www.cnie.org/nle/clim-3.html. This document is a Congressional Research Service Report for Congress, and was written by Susan R. Fletcher, Senior Analyst in International Environmental Policy, and was last updated March 2000.

Regional & Local Atmospheric Environmental Concerns

While the problems of stratospheric ozone depletion and climate change are global in scale, acid deposition, another air-related environmental problem, is regional.

Regional - Acid Rain

The composition of rain and snow depends upon the gases or other agents present in region of the atmosphere in which the clouds are formed. When water forms clouds, various chemicals and dust particles (both naturally-occurring and anthropogenic) are dissolved or trapped in the droplets, and eventually deposited back onto the ground.

Rain or snow can be acidic due to natural causes. However, the range of acidity varies, and precipitation may even be alkaline (or basic) in some places. "Natural" acidity occurs because of dissolved organic oxides (like CO_2) and sulfur compounds from decaying biomass. Acidity also occurs as a result of more extreme phenomena like volcanic eruptions, which spew large quantities of CO_2, H_2S, and SO_2 into the air.

When acidic gases are emitted into the air, they react with water vapor molecules and form acid droplets. These droplets deposit as drops in what is known as acid rain (or acid precipitation). Some dry deposition also occurs, in which the NOx and SOx particles cling to dust and are deposited on surfaces. These two processes are generally referred to as acid deposition.

Increasingly large and routine emissions of acidic gases from human activity result in a significant increase in acid deposition, making it a significant regional environmental problem. Most prominent among the anthropogenic acidic gases are oxides of sulfur and oxides of nitrogen. Both nitrogen and sulfur have many oxides, varying in the amount of oxygen relative to nitrogen or sulfur, and they are generally denoted by NOx and SOx.

Currently, approximately half of the compounds that add acidity to rain are anthropogenic. One major source of these compounds is the smelting of sulfur-based ores in metal processing. A classic case of acid deposition impacts due to metal processing occurred in Sudbury in Ontario, Canada. There, open roasting of nickel-copper ores released sulfur dioxide that destroyed much of the vegetation in the area.

The other major source of compounds causing acid deposition is the combustion of fossil fuels. Fossil fuels are used in the production of electricity and in powering automobiles. All fossil fuels contain some sulfur. Coal contains varying amounts of sulfur, depending on the region of its origin. The sulfur in natural gas is removed during refinement.

Acid deposition has several consequences. It alters the pH in the water cycle, thus upsetting the local ecological balance. This alteration stresses, and can even destroy, vegetation and aquatic animals. Acid deposition is injurious to life because of corrosive effects on the body when inhaled. It also corrodes marble and other stones, causing "pitting" of statues and other historical monuments. Examples of these harmful effects seen in eastern parts of the United States include loss of some trees and fish in Appalachian forests and streams and pitting of monuments in the Gettysburg National Park.

The problem of acid deposition came to be recognized in the 1970's, and since then many laws have been passed to regulate air pollution in the U.S. and Canada. Also, some technological measures have been taken to reduce acid precipitation, including "clean coal" technologies, which clean coal of sulfur before combustion, and catalytic converters in the exhaust systems of automobiles, which transforms hydrocarbons, carbon monoxide, and nitrous oxides into water, carbon dioxide, nitrogen, and oxygen.

Local - Photochemical Smog & Tropospheric Ozone

Smog (**Sm**oke and f**og**) was a phenomenon recognized in the early 1950's when thousands of deaths and intense respiratory problems occurred in London, England; Donora, Pennsylvania; and cities in other countries all over the industrialized world. The city of Los Angeles and parts of Southern California have now come to be associated with smog.

There are different sources of smog. Early incidents of smog arose primarily from the combustion of coal with high sulfur content. The combustion resulted in the reaction of sulfur dioxide (SO_2), nitrogen oxides, and dust particles reacted to form particles and droplets of sulfates (SO_4^{2-}) and nitrates (NO_3^-). This mixture of smoke and fog clouded the atmosphere, and irritated the mucous membranes and the eyes of the people exposed to it.

A new version of smog is the photochemical smog which comes from reactions between the solar radiation (ultraviolet that gets through the stratospheric ozone layer and visible light) and gases produced by various industrial processes. When solar radiation acts on some of the gases emitted from some processes, particularly exhaust from vehicles, ozone and other gases are produced in the troposphere. This process is called a photochemical reaction because it is a chemical reaction between light (*photo*) and the chemicals in exhaust gases. Predominant among the gases undergoing photochemical reactions are hydrocarbons (compounds of hydrogen and carbon), oxides of nitrogen, NO (nitric oxide) and NO_2 (nitrogen dioxide). Photochemical smog is an increasing problem in cities with high traffic. It is often associated with Los Angeles and Mexico City because of the large amounts of traffic and bright sunlight there.

Photochemical reactions produce a variety of gases, many of which are harmful to health. They often cause simple irritation of the mucous membranes and eyes because of their acidic nature, and sometimes result in more serious respiratory problems because they overpower the immune and respiratory systems.

Among the gases produced in the photochemical smog are ozone and peroxyacetyl nitrate (often referred to as PAN). The following reactions produce ground-level ozone:

$NO_2 + uv \rightarrow NO + O$
$O + O_2$ (+ catalyst) $\rightarrow O_3$ (+ catalyst)

Numerous other reactions also occur, producing a variety of highly reactive compounds, and recycling nitrogen dioxide to produce more of the reactions! A catalyst is a compound that helps speed a reaction while maintaining its own amount and composition being the same before and after the reaction. Carbon monoxide, which is present in plenty in vehicle exhaust, is a good catalyst for the above reaction.

Also note that sunlight is a requisite for this reaction. Figure 13 shows the time course of the tropospheric ozone formation in a typical high traffic, sunny city. It shows the ozone buildup, after the exhaust gases and sunlight have had time to "cook" the reactive mixture that makes up the photochemical smog.

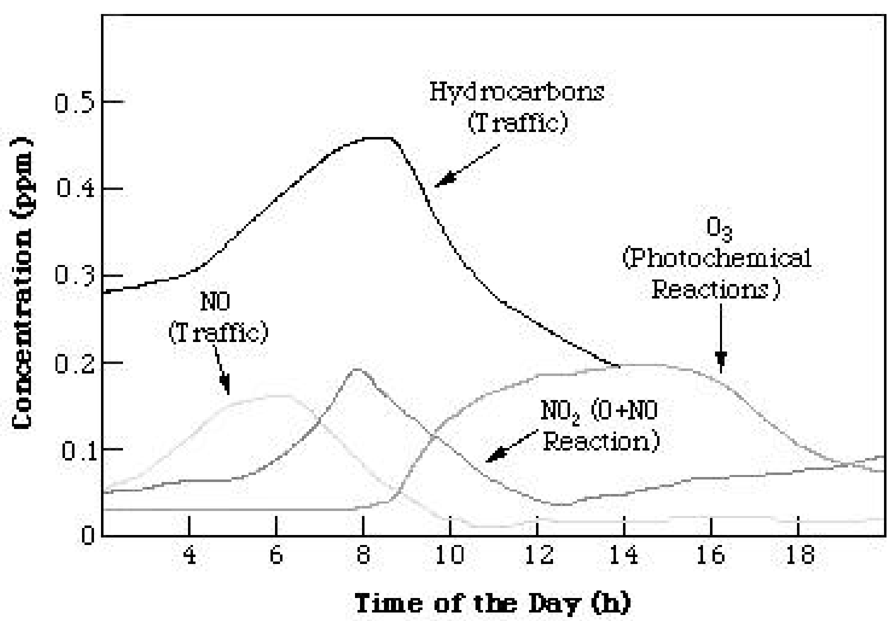

Figure 13: Rise of ozone smog toward mid day.

So, ozone whose presence in the stratosphere has a protective effect on us, becomes a health problem when it is present in our layer of the atmosphere and we breathe it in. Because of this, the tropospheric ozone is often referred to as "bad ozone" and the stratospheric ozone as "good ozone".

Local - Urban Heat Islands

"Urban heat islands" are a sort of localized enhanced greenhouse phenomenon. They are simply built-up areas of city that are significantly warmer than the surrounding area of countryside. The difference in temperature comes from the fact that buildings, paved surfaces, and other man-made structures absorb higher amounts of sunlight than most natural objects. This energy is re-radiated at longer wavelengths during the night, and atmospheric pollution in the form of heat-absorbing gases form a "local" atmosphere much like the glass of a greenhouse, trapping in the heat.

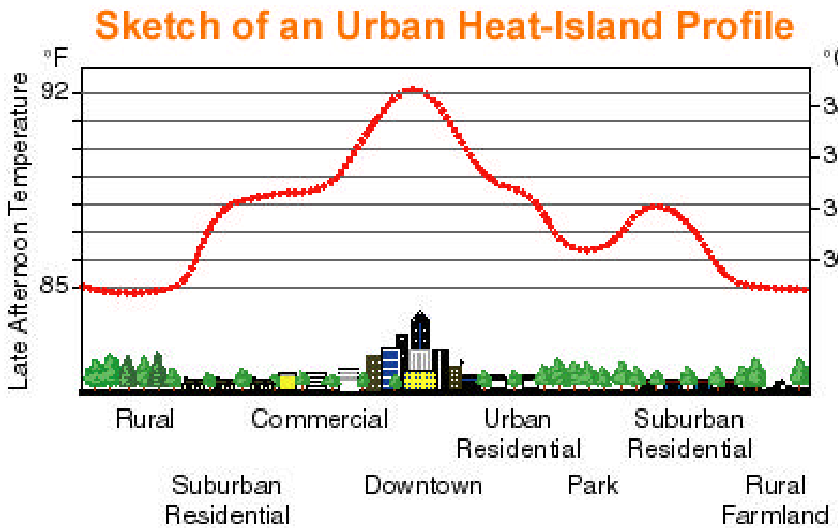

Figure 14: Graph of temperatures showing urban heat island effect.
(from Lawrence Berkeley National Laboratory)

Meteorologists have noticed that metropolitan areas are creating their own weather patterns at night due to the collision of cool air from the surrounding area with the warmer city air. It is important to note that urban heat islands are a localized effect, whereas the general atmospheric greenhouse effect is global in extent.

Effects of Air Pollution

Air pollution has numerous impacts on ecosystems and human health. At an extreme is the devastation of areas like Sudbury, Canada, from acid rain and large areas of the Black Forest regions in East Germany from decades of unchecked industrial pollution. Human health effects include respiratory problems as well as effects on the eyes and skin. Different effects are associated with different concentrations of the pollutant. Although people react much more sharply to odors in the air and early air pollution standards were set by aesthetic conditions, there are odorless but dangerous pollutants such as CO. Maximum allowed (or permissible) concentrations (MAC or MPC) are usually set on a citywide, regional, or statewide basis to control air pollution. Emergency measures, such as closing industrial plants, limiting auto use, and advising children or people with respiratory problems to remain indoors, are sometimes taken when there are dangerous pollutant levels.

Acidic oxides such as Sox and NOx cause corrosions of many materials such as metals and limestone and can cause damage to structures. Typical MAC of SO_2 is about 0.3 ppm. NO_2 changes vegetation. Both of these can contribute to the development of respiratory disease.

Carbon monoxide is formed by rapid burning of carbon in an environment with insufficient oxygen. CO in concentrations of 2000 ppm causes death by interfering with the distribution of oxygen in the body. Hemoglobin is the molecule in the blood that carries O_2 to all parts of the body. The CO molecule has the same overall shape as the O_2 and fits into the part of the hemoglobin that normally carries O_2, thus making the space unavailable for O_2. The compound carboxyhemoglobin can affect the ability to track and see clearly if breathed at 30 ppm for 8 hours. At that rate of inhalation, 10% of the hemoglobin can become carboxyhemoglobin.

Ozone has a strong odor even at 0.02 ppm. it causes damage to biological tissues and to some materials like rubber. Ozone irritates the eyes and upper respiratory tract at concentrations of 0.1 ppm.

Lead, dust, soot, and other materials ejected in various processes can become airborne. Particulates in the air can also cause health problems. Visibility is reduced when particulate concentration are high. Asthma, an in creasing problem in children and in populations and other respiratory problems are aggravated by inhaled particulates.

APPENDIX I – GREENHOUSE GASES

We noted earlier that water vapor (H_2O) and carbon dioxide (CO_2) are two of the major greenhouse gases. Both of these molecules are present on Earth naturally, their amounts having evolved to steady levels as a total effect of plant and animal life. There are several other gases that contribute to the greenhouse effect. Most prominent among these are methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons. Each gas is present in the atmosphere at a different concentration. In addition to knowing the concentration of the greenhouse gas, it is important to understand that each gas has a different relative greenhouse efficiency. In other words, some gases are better at absorbing the solar radiation than others, and therefore have a greater overall impact on the greenhouse effect. As a measure of this efficiency, greenhouse gases are often assigned a value for "Global Warming Potential" (GWP). This value is simply a comparison of the efficiency of a gas relative to CO_2 over a time span of 100 years. Therefore a gas with a GWP of 20 is 20 times more efficient at retaining heat than CO_2 over a 100 year time period.

Another important characteristic to examine when considering the potential damage of a greenhouse gas is the average time they remain in the atmosphere once emitted. Policies made now that reduce industrial and other emissions of greenhouse gases take years to result in changes in the atmosphere and its nature. In fact, scientists have stated that no matter how aggressively greenhouse gas emissions are restricted and reduced now, "the planet and the nation are certain to experience more than a century of climate change, due to the long lifetime of greenhouse gases already in the atmosphere and the momentum of the climate system." (From Climate Change Impacts on the United States, Cambridge University Press: 2000.)

Of all the greenhouse gases, **carbon dioxide** is present at the highest concentration by far. Based on 1990 concentrations, carbon dioxide is said to be responsible for almost 60% of the total greenhouse effect when efficiency and concentration are considered. Its concentration is increasing in the atmosphere due in large part to the extensive burning of coal and other fossil fuels for energy production. Another cause of CO_2 increase is the destruction of large areas of trees that leads to a reduction in use of carbon dioxide for photosynthesis.

Methane is present in the atmosphere at less than 1% the levels of carbon dioxide, however it is 25 times more efficient as a greenhouse gas. It contributes to a little over 10% of the total greenhouse effect based on current concentrations. The primary anthropogenic sources are combustion of fossil fuel, and the decomposition of organic materials associated with wetlands, rice paddies, and livestock manure.

Nitrous oxide also occurs in low concentrations relative to carbon dioxide, but it is 230 times more efficient as a greenhouse gas. These factors combine to make it a 6% contributor to total the greenhouse effect. The primary anthropogenic sources are fossil fuel combustion, fertilizers, and deforestation.

The only major greenhouse gases that are not naturally occurring are the **chlorofluorocarbons**. They come solely from anthropogenic sources such as the production and/or use of foams, aerosols, refrigerants, and solvents. They are present at an extremely low concentration in the atmosphere, however they are 15,000 times more efficient as a greenhouse gas relative to carbon dioxide. As a result, they contribute to approximately 25% of the total greenhouse effect based on 1990 concentrations.

Table 3 lists the major greenhouse gases, their emission levels and sources, and the approximate amount of time they remain in the atmosphere once they are emitted. It also gives their approximate concentrations 100 years ago, today, and projected concentration for the year 2030. Note that concentrations are given in parts per billion (ppb), referring to the proportion of molecules of the gas per billion molecules in the atmosphere. For example, the concentration of CO_2 today is 350,000 ppb, meaning that for every billion molecules in the atmosphere, there are 350,000 molecules of CO_2.

Gas	Major Anthropogenic Sources	Amount Released per Year (millions of tons)	Average Time in the Atmosphere	Global Warming Potential* (over 100 years)	Pre-industrial Concentration (around 1860) (ppb)	Average Concentration now (ppb)	Expected Concentration in 2030 (ppb)
CO_2	Burning of Fossil Fuels	5,500	100 years	1	290,000	350,000	500,000
CH_4	Fossil Fuel Production, Rice Fields	500	10 years	21	850	1,700	2,300
N_2O	Fertilizers, Deforestatio, Burning Biomass	30	days	310	.001 to 7	.001 to 50	.001 to 50
CFCs	Aerosol Sprays, Refrigerants	1	60 to 100 years	1500-8100	0	about 3	2.4 to 6

Table 3: Summary of greenhouse gases.

APPENDIX II – PREDICTING IMPACTS OF CLIMATE CHANGE

Scientists have developed several computer-run simulations, or models, that combine and express in mathematical form what we know about the processes that control the atmospheric and hydrologic systems. The most advanced climate models are called General Circulation Models, or GCM's. These models are the primary tools used by scientists to try to predict the impacts of increased greenhouse gas concentration. The strength of these models is their ability to replicate input-response activities and relationships within complex systems that are far too elaborate for simple interpretation or logic. They have the ability to integrate various feedback processes in order to determine their effects on overall impact, and quickly generate different scenarios under varied assumptions about human activities.

A feedback can be defined as a direct result of a given process that either magnifies (positive feedback) or diminishes (negative feedback) the total effect of that very same process. One example of a positive feedback of global warming is the potential impact of increased concentration of water vapor in the atmosphere. As the oceans and atmosphere warm, the rate evaporation increases, causing more water vapor to accumulate in the atmosphere. As we noted earlier, water vapor is itself a greenhouse gas, causing even more heat to be trapped in the troposphere. Thus global warming is magnified by a result of its own existence.

Another example is the possibility of melting arctic ice caps releasing large amounts of carbon into the atmosphere. Ice caps are a strong "sink" for carbon, storing the equivalent of almost one-third of the total carbon in Earth's atmosphere. As the Earth's temperature rises, and arctic permafrost and tundra melt, the carbon will be released into the atmosphere. The result is once again more heat being trapped and an even further increased global temperature.

To date, there are no known negative feedbacks resulting directly from increased greenhouse gas concentrations. There is, however, a negative feedback closely related to the burning of fossil fuels, particularly coal. Microscopic airborne particles called "aerosols" exist naturally in the atmosphere, but their concentration has also shown a dramatic increase since pre-industrial times. Sulfate aerosols (or aerosols containing sulfur and oxygen) have a known cooling influence on the atmosphere, due to the fact that they reflect some incoming solar radiation back into space before it hits the surface of the Earth. Therefore, the increase in sulfate aerosols in the atmosphere could offset some of the warming resulting from increased greenhouse gas concentrations, but it is difficult to predict how much.

Unfortunately, there are still major areas of uncertainty that render the climate-modeling process highly complicated and far from totally accurate. Eric J. Barron, chair of the USGCRP Forum on Global Change Modeling, writes:

> "Predictions of future climate are imperfect because they are limited by significant uncertainties that stem from: (1) the natural variability of climate; (2) our inability to predict accurately future greenhouse-gas and aerosol emissions; (3) the potential for unpredicted or unrecognized factors, such as volcanic eruptions or new or unknown human influences, to perturb atmospheric conditions; and (4) our as-yet incomplete understanding of the total climate system."
>
> --(from "Climate Models: How Reliable are Their Predictions?" *Consequences*, Vol. 1 No. 3, 1995.)

Continuous improvements to the bodies of knowledge in each of these areas leads to more and more accurate modeling of the global climate. Currently, scientists use several different models as cross-checks to create possible alternative scenarios of the future. For some aspects of climate (such as temperature rise and occurrence of precipitation in heavy and extreme events), virtually all climate models concur on consistent results, lending a high degree of confidence to their accuracy. For other aspects, model results differ. For example, some models project extensive and frequent drought in the US, while others do not. These scenarios offer differing yet plausible alternative futures, and help detect areas in which the models need improvement.

Predictions

Overall, the models predict that global average surface temperature will increase anywhere from 3 to 6° F in the 21st century, with change in the US ranging from 3 to 9° F. Scientists have used scenarios of global change to predict several impacts such as:

- sea level rise
- shifts in population and farming centers
- rise in water temperature
- increase in storm frequency and severity
- extensive droughts
- threats to or loss of vulnerable yet valuable ecosystems (barrier islands, coastal forests, alpine meadows, coral reefs, tropical mountain forests, and so on.)

Below is a list of the key findings of the National Assessment Synthesis Team regarding climate change impacts on the US. The NAST is a committee of experts drawn from governments, universities, industry and non-governmental organizations (or NGO's) assembled to synthesize, evaluate and report on what is presently known about possible impacts of climate variability and change. Their Assessment was called for by a 1990 law, and has been conducted under the United States Global Change Research Program. The Assessment Overview, as well as the more detailed Foundation Report, can be found at http://www.gcrio.org/NationalAssessment/index.html.

1. **Increased warming** Assuming continued growth in world greenhouse gas emissions, the primary climate models used in this Assessment project that temperatures in the US will rise 5-9°F (3-5°C) on average in the next 100 years. A wider range of outcomes is possible.
2. **Differing regional impacts** Climate change will vary widely across the US. Temperature increases will vary somewhat from one region to the next. Heavy and extreme precipitation events are likely to become more frequent, yet some regions will get drier. The potential impacts of climate change will also vary widely across the nation.
3. **Vulnerable ecosystems** Many ecosystems are highly vulnerable to the projected rate and magnitude of climate change. A few, such as alpine meadows in the Rocky Mountains and some barrier islands, are likely to disappear entirely in some areas. Others, such as forests of the Southeast, are likely to experience major species shifts or break up into a mosaic of grasslands, woodlands, and forests. The goods and services lost through the disappearance or fragmentation of certain ecosystems are likely to be costly or impossible to replace.
4. **Widespread water concerns** Water is an issue in every region, but the nature of the vulnerabilities varies. Drought is an important concern in every region. Floods and water quality are concerns in many regions. Snowpack changes are especially important in the West, Pacific Northwest, and Alaska
5. **Secure food supply** At the national level, the agriculture sector is likely to be able to adapt to climate change. Overall, US crop productivity is very likely to increase over the next few decades, but the gains will not be uniform across the nation. Falling prices and competitive pressures are very likely to stress some farmers, while benefiting consumers.
6. **Near-term increase in forest growth** Forest productivity is likely to increase over then next several decades in some areas as trees respond to higher carbon dioxide levels. Over the longer term, changes in larger-scale processes such as fire, insects, droughts, and disease will possibly decrease forest productivity. In addition, climate change is likely to cause long-term shifts in forest species, such as sugar maples moving north out of the US.
7. **Increased damage in coastal and permafrost areas** Climate change and the resulting rise in sea level are likely to exacerbate threats to buildings, roads, powerlines, and other infrastructure in climatically sensitive places. For example, infrastructure damage is related to permafrost melting in Alaska, and to sea-level rise and storm surge in low-lying coastal areas.
8. **Adaptation determines health outcomes** A range of negative health impacts is possible from climate change, but adaptation is likely to help protect much of the US population. Maintaining our nation's public health and community infrastructure, from water treatment systems to emergency shelters, will be important form minimizing the impacts of water-borne diseases, heat stress, air pollution, extreme weather events, and diseases transmitted by insects, ticks, and rodents.
9. **Other stresses magnified by climate change** Climate change will very likely magnify the cumulative impacts of other stresses such as air and water pollution and habitat destruction due to human development patterns. For some systems, such as coral reefs, the combined effects of climate change and other stresses are very likely to exceed a critical threshold, bringing large, possibly irreversible impacts.
10. **Uncertainties remain and surprises are expected** Significant uncertainties remain in the science underlying regional climate changes and their impacts. Further research would improve understanding and our ability to project societal and ecosystem impacts, and provide the public with additional useful information about options for adaptation. However, it is likely that some aspects and impacts of climate change will be totally unanticipated as complex systems respond to ongoing climate change in unforeseeable ways.