Section 3. Climate and the General Circulation

Causes of Climate Change

Why the earth's climate changes is not totally understood. Many theories attempt to explain the changing climate, but no single theory alone can satisfactorily account for all the climatic variations of the geologic past.

Why hasn't the riddle of a fluctuating climate been completely solved? One major problem facing any comprehensive theory is the intricate interrelationship of the elements involved. For example, if temperature changes, many other elements may be altered as well. The interactions among the atmosphere, the oceans, and the ice are extremely complex and the number of possible interactions among these systems is enormous. No climatic element within the system is isolated from the others. With this in mind, we will first investigate a how feedback systems work; then we will consider some of the current theories of climatic change.

Climate Change and Feedback Mechanisms

The earth-atmosphere system is in a delicate balance between incoming and outgoing energy. If this balance is upset, even slightly, global climate can undergo a series of complicated changes.

Let's assume that the earth-atmosphere system has been disturbed to the point that the earth has entered a slow warming trend. Over the years the temperature slowly rises, and water from the oceans rapidly evaporate into the warmer air. The increased quantity of water vapor absorbs more of the earths infrared energy, thus strengthening the atmospheric greenhouse effect. This raises the air temperature even more, which, in turn, further increases the evaporation rate. The greenhouse effect becomes even stronger and the air temperature rises even more. This situation is known as the water **vapor-temperature rise feedback**. It represents a **positive feedback mechanism** because the initial increase in temperature is reinforced by the other processes. If this feedback were left unchecked, the earth's temperature would increase until the oceans evaporated away. Such a chain reaction is called a *runaway greenhouse effect*. The earth-atmosphere system has a number of checks and balances that help it readjust into a new equilibrium. Hence, there is no evidence that a runaway greenhouse effect ever occurred on earth, and it is not very likely that it will occur in the future.

Another positive feedback mechanism is the snow-albedo feedback, where an increase in global surface air temperature might cause snow and ice to melt in polar latitudes. This melting would reduce the albedo (reflectivity) of the surface, allowing more solar energy to reach the surface, which would further raise the temperature. But helping to counteract the positive feedback mechanisms are **negative feedback mechanisms**—those that tend to weaken the interactions among the variables rather than reinforce them. Suppose, for example, that as the surface warms more water evaporates from the oceans and global low cloudiness increases. Low clouds tend to reflect a large percentage of incoming sunlight, and with less solar energy to heat the surface, the warming slows.

All feedback mechanisms work simultaneously and in both directions. We just saw that the snow-albedo feedback produces a positive feedback on a warming planet, but it can produce a positive feedback on a cooling planet as well. For example, suppose the earth were in a slow global cooling trend that lasted for hundreds or even thousands of years. Lower temperatures might allow for a greater snow cover in middle and high latitudes, which would increase the albedo of the surface so that much of the incident sunlight would be reflected back to space. Less sunlight absorbed at the surface might cause a further drop in temperature. This action might further increase the snow cover, lowering the temperature even more. If left unchecked, the snow-albedo feedback would produce a runaway ice age which, of course, is not likely on earth because other feedback mechanisms in the atmospheric system are constantly working to moderate the magnitude of the cooling.

Climate Change, Plate Tectonics, and Mountain Building

During the geologic past, the earth's surface has undergone extensive modifications. One involves the slow shifting of the continents and the ocean floors. This motion is explained in the widely acclaimed **theory of plate tectonics** (formerly called the *theory of continental drift*). According to this theory, the earth's outer shell is composed of huge plates that fit together like pieces of a jigsaw puzzle. The plates, which slide over a partially molten zone below them, move in relation to one another. Continents are embedded in the plates and move along like luggage riding piggyback on a conveyer belt. The rate of motion is extremely slow, only a few centimeters per year.

Besides providing insights into many geological processes, plate tectonics also helps to explain past climates. For example, we find glacial features near sea level in Africa today, suggesting that the area underwent a period of glaciation hundreds of millions of years ago. Were temperatures at low elevations near the equator ever cold enough to produce ice sheets? Probably not. The ice sheets formed when this land mass was located at a much higher latitude. Over the many millions of years since then, the land has slowly moved to its present position. Along the same line, we can see how the fossil remains of tropical vegetation can be found under layers of ice in polar regions today.

According to plate tectonics, the now existing continents were at one time joined together in a single huge continent, which broke apart. Its pieces slowly moved across the face of the earth, thus changing the distribution of continents and ocean basins (see Figure 1). Some scientists feel that, when land masses are concentrated in middle and high latitudes, ice sheets are more likely to form. During these times, there is a greater likelihood that more sunlight will be reflected back into space and that the snow-albedo feedback mechanism mentioned earlier will amplify the cooling.

The various arrangements of the continents may also influence the path of ocean currents. This would alter the transport of heat from low to high latitudes and change both the global wind system and the climate in middle and high latitudes. As an example, suppose that plate movement "pinches off" a rather large body of high latitude ocean water such that the transport of warm water into the region is cut off. In winter, the surface water would eventually freeze over with ice. This freezing would, in turn, reduce the amount of sensible and latent heat given up to the atmosphere. Furthermore, the ice allows snow to accumulate on top of it, thereby setting up conditions that could lead to even lower temperatures.

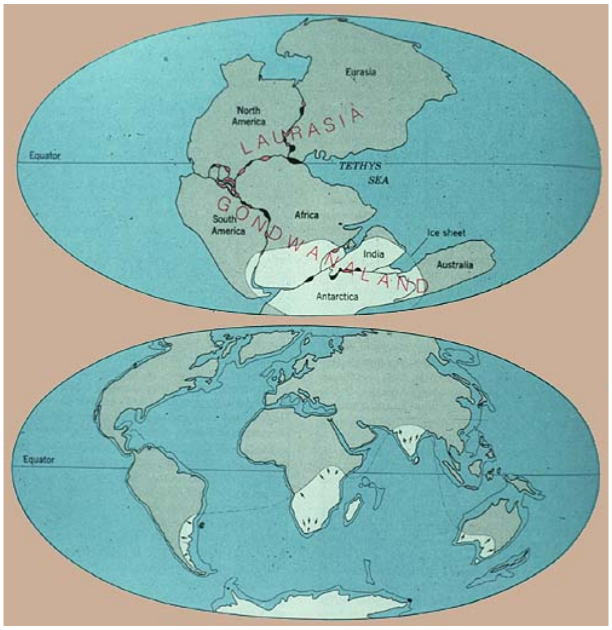

Figure 1: Configuration of continental land masses during the Permian and today.

Climate Change and Variations in the Earth's Orbit

A popular theory ascribing climatic changes to variations in the earth's orbit is the **Milankovitch theory**, named for the astronomer Milutin Milankovitch, who first proposed the idea in the 1930s. The basic premise of this theory is that, as the earth travels through space, three separate cyclic movements combine to produce variations in the amount of solar energy that falls on the earth.

The first cycle deals with changes in the shape (**eccentricity**) of the earth's orbit as the earth revolves about the sun. Notice in Figure 2 that the earth's orbit changes from being elliptical to being nearly circular. To go from less elliptical to more elliptical and back again takes about 100,000 years. The greater the eccentricity of the orbit, the greater the variation in solar energy received at the top of the atmosphere between the earth's closest and farthest approach to the sun.

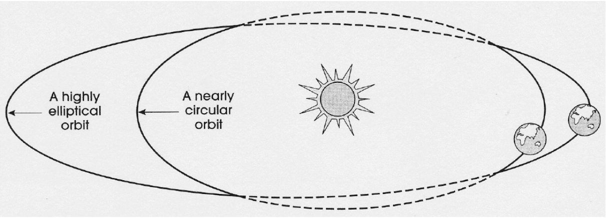

Figure 2: Changes in eccentricity of the Earth's orbit. The period is about 100,000 years.

Presently, we are in a period of low eccentricity. The earth is closer to the sun in January and farther away in July. The difference in distance (which only amounts to about 3 percent) is responsible for a nearly 7% increase in the solar energy received at the top of the atmosphere from July to January. When the difference in distance is 9% (a highly eccentric orbit), the difference in solar energy received will be on the order of 20%. In addition, the more eccentric orbit will change the length of seasons in each hemisphere by changing the length of time between the vernal and autumnal equinoxes.

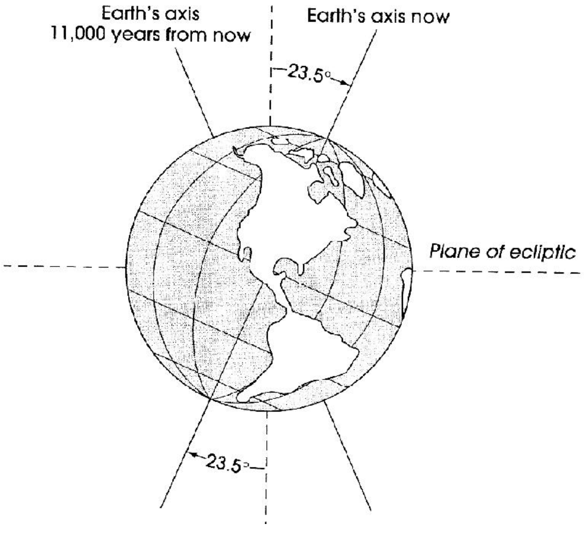

Figure 3: Changes in axial precession. The period is about 23,000 years.

The second cycle takes into account the fact that, as the earth rotates on its axis, it wobbles like a spinning top. This wobble, known as the **precession** of the earth's axis, occurs in a cycle of about 23,000 years. Presently, the earth is closer to the sun in January and farther away in July. Due to precession, the reverse will be true in about 11,000 years (see Figure 3). In about 23,000 years we will be back to where we are today. This means, of course, that if everything else remains the same, 11,000 years from now seasonal variations in the Northern Hemisphere should be greater than at present. The opposite would be true for the Southern Hemisphere.

The third cycle takes about 41,000 years to complete and relates to the changes in tilt (**obliquity**) of the earth as it orbits the sun (see Figure 4). Presently, the earth's orbital tilt is 23 1/2°, but during the 41,000-year cycle the tilt varies from about 22° to 24 1/2°. The smaller the tilt, the less seasonal variation there is between summer and winter in middle and high latitudes. Thus, winters tend to be milder and summers cooler. During the warmer winters, more snow would probably fall in polar regions due to the air's increased capacity for water vapor. And during the cooler summers less snow would melt. As a consequence, the periods of smaller tilt would tend to promote the formation of glaciers in high latitudes. In fact, when all of the cycles are taken into account, the present trend should be toward a cooler climate over the Northern Hemisphere, with extensive glaciation.

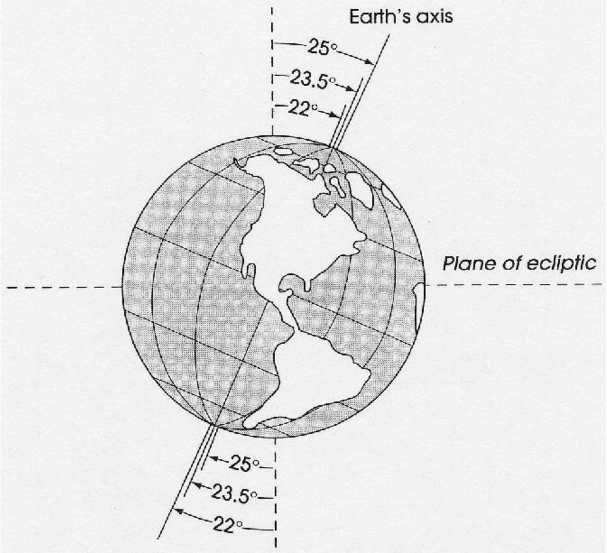

Figure 4: Changes in the angle of Earth's axis with the plane of the ecliptic. The period is 41,000 years.

In summary, the Milankovitch cycles that combine to produce variations in solar radiation received at the earth's surface include:

1. changes in the shape (*eccentricity*) of the earth's orbit about the sun
2. *precession* of the earth's axis of rotation, or wobbling
3. changes in the tilt (*obliquity*) of the earth's axis

In the 1970s, scientists of the CLIMAP project found strong evidence in deep-ocean sediments that variations in climate during the past several hundred thousand years were closely associated with the Milankovitch cycles. Recent studies have even strengthened this premise. For example, studies conclude that during the past 800,000 years, ice sheets have peaked about every 100,000 years. This conclusion corresponds naturally to variations in the earth's eccentricity. Superimposed on this situation are smaller ice advances that show up at intervals of about 41,000 years and 23,000 years. It appears, then, that eccentricity is the *forcing factor*—the external cause—for the frequency of glaciation, as it appears to control the severity of the climatic variation.

But orbital changes alone are probably not totally responsible for ice buildup and retreat. Evidence (from trapped air bubbles in the ice sheets of Greenland and Antarctica representing thousands of years of snow accumulation) reveals that CO_2 levels were about 30 percent lower during colder glacial periods than during warmer interglacial periods (see Figure 5). This knowledge suggests that lower atmospheric CO_2 levels may have had the effect of amplifying the cooling initiated by the orbital changes. Likewise, increasing CO_2 levels at the end of the glacial period may have accounted for the rapid melting of the ice sheets. Just why atmospheric CO_2 levels have varied as glaciers expanded and contracted stirs up much debate, but it appears to be due to changes in biological activity taking place in the oceans.

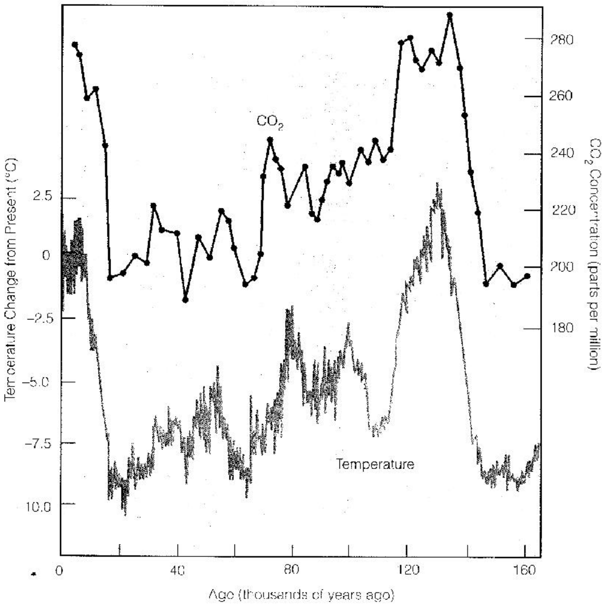

Figure 5: Analysis of trapped bubbles of ancient air in the polar ice sheet at Vostok station in Antarctica reveals that over the past 160,000 years, CO_2 levels (upper curve) correlate well with air temperature changes (bottom curve).

Perhaps, also, changing levels of CO_2 indicate a shift in ocean circulation patterns. Such shifts, brought on by changes in precipitation and evaporation rates, may alter the distribution of heat energy around the world. Alteration wrought in this manner could, in turn, affect the global circulation of winds, which may explain why alpine glaciers in the Southern Hemisphere expanded and contracted in tune with Northern Hemisphere glaciers during the last ice age, even though the Southern Hemisphere (according to the Milankovitch cycles) was not in an orbital position for glaciation.

Still other factors may work in conjunction with the earth's orbital changes to explain the temperature variations between glacial and interglacial periods. Some of these are:

1. the amount of dust in the atmosphere
2. the reflectivity of the ice sheets
3. the concentration of other trace gases, such as methane
4. the changing characteristics of clouds

5. the rebounding of land, having been depressed by ice

Hence, the Milankovitch cycles, in association with other natural factors, may explain the advance and retreat of ice over periods of 10,000 to 100,000 years. But what caused the Ice Age to begin in the first place? And why have periods of glaciation been so infrequent during geologic time? The Milankovitch theory does not attempt to answer these questions.

Climate Change and Atmospheric Particles

Tiny liquid and solid particles (*aerosols*) that enter the atmosphere from both anthropogenic (human induced) and natural sources can have an effect on climate. The effect, however, is exceedingly complex and depends upon a number of factors, such as the particle's size, shape, color, and vertical distribution above the surface. In this section, we will first examine aerosols in the lower atmosphere. Then we will examine the effect that volcanic aerosols in the stratosphere have on climate.

Aerosols in the Troposphere Aerosols enter the lower atmosphere in a variety of ways—from factory and auto emissions, agricultural burning, and wildland fires. Once in the atmosphere, aerosol particles absorb sunlight and infrared radiation from the earth's surface. Hence, they tend to warm the air around them. These same particles reflect and scatter incoming sunlight back to space. This effect reduces the amount of shortwave energy that reaches the surface, causing a cooling of surface air during the daytime. At night, the absorption and emission of longwave infrared radiation produce a net warming of the surface air.

In recent years, the effect of highly reflective *sulfate aerosols* on climate has been extensively researched. In the lower atmosphere, the majority of these particles come from the combustion of sulfur-containing fossil fuels. Sulfur pollution, which has more than doubled globally since preindustrial times, enters the atmosphere mainly as sulfur dioxide gas. There, it transforms into tiny sulfate droplets or particles. Since these aerosols usually remain in the atmosphere for only a few days, they do not have time to spread around the globe. Hence, they are not well mixed and their effect is felt mostly over the Northern Hemisphere, especially over polluted regions. Over the oceans, a major source of sulfate aerosols comes from tiny drifting aquatic plants—phytoplankton—that produce *dimethylsulphide* (DMS). The DMS slowly diffuses into the atmosphere where it oxidizes to form sulfur dioxide, which in turn converts to sulfate aerosols.

Sulfate aerosols not only scatter incoming sunlight back to space, but they also serve as cloud condensation nuclei. Consequently, they have the potential for altering the physical characteristics of clouds. For example, if the number of sulfate aerosols and, hence, condensation nuclei inside a cloud should increase, the cloud would have to share its available moisture with the added nuclei, a situation that should produce many more (but smaller) cloud droplets. The greater number of droplets would reflect more sunlight and have the effect of brightening the cloud and reducing the amount of sunlight that reaches the surface.

In summary, sulfate aerosols reflect incoming sunlight, which tends to lower the earth's surface temperature during the day. Studies estimate that over the Northern Hemisphere this cooling effect may be about equal to the warming induced by CO_2. Sulfate aerosols may also modify clouds by increasing their reflectivity. Because sulfate pollution has increased significantly over industrialized areas of eastern Europe and northeastern North America the cooling effect brought on by these particles may explain: (1) why the Northern Hemisphere has warmed less than the Southern Hemisphere during the past several decades, (2) why the United States has experienced little warming compared to the rest of the world, and (3) why most of the global warming has occurred at night and not during the day, especially over polluted areas. Research is still being done, and the overall effect of tropospheric aerosols on the climate system is not totally understood.

Volcanic Eruptions and Aerosols in the Stratosphere Volcanic eruptions can have a definitive impact on climate. During volcanic eruptions, fine particles of ash and dust (as well as gases) can be ejected into the stratosphere. Scientists agree that the volcanic eruptions having the greatest impact on climate are those rich in sulfur gases. These gases, over a period of about 2 months combine with water vapor in the presence of sunlight to produce tiny, bright sulfuric acid particles that grow in size, forming a dense layer of haze. As heavier particles fall out of the stratosphere, new particles form. And so the haze layer may reside in the stratosphere for several years, absorbing and reflecting back to space a portion of the sun's incoming energy. This effect can cause a warming of the stratosphere and a cooling of the global surface air temperature, especially in the hemisphere where the eruption occurs.

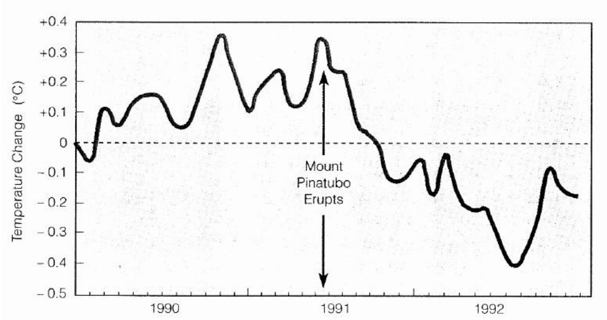

Figure 6: Changes in average global air temperature from 1990–1992. After the eruption of Mount Pinatubo in June, 1991, the average global temperature by July, 1992, decreased by almost 0.5°C (0.9°F) from the 1981–1990 average (dashed line).

The two largest volcanic eruptions so far this century in terms of their sulfur-rich veil, were that of El Chichón in Mexico during April, 1982, and Mount Pinatubo in the Philippines during June, 1991. Mount Pinatubo ejected an estimated 20 million tons of sulfur dioxide into the stratosphere (more than twice that of El Chichón) that gradually worked its way around the globe. For major eruptions such as this one, mathematical models predict that average hemispheric temperatures can drop by about 0.2° to 0.5°C or more for from one to three years after the eruption.

Shortly after the eruption of Mount Pinatubo, satellites began to detect a several percent increase in the amount of sunlight reflected by the earth's atmosphere. At the same time, global temperatures began to drop, and by July, 1992, the average global air temperature had decreased by about 0.8°C (1.5°F) (see Figure 6). The satellite data, coupled with the drop in global temperature, provided conclusive evidence that sulfur-rich volcanic eruptions can cool the earth. The cooling might even have been greater had the eruption not coincided with a major El Niño event that began in 1990 and peaked in 1992.

Volcanic eruptions rich in sulfur warm the lower stratosphere. During the winter, when sunlight is most intense over low latitudes and very little sunlight reaches high latitudes, the tropical stratosphere can become much warmer than the polar stratosphere. This situation produces a strong horizontal pressure gradient and strong west-to-east (zonal) stratospheric winds. These winds apparently work their way down into the upper troposphere, where they direct milder maritime surface air from off the ocean onto the continents. The milder ocean air produces warmer winters over Northern Hemisphere continents during the first or second winter after the eruption occurs. Meanwhile, in the tropics and subtropics, the stratospheric aerosols block sunlight from reaching the surface and produce cooling.

Climate Change and Variations in Solar Output

In the past, it was thought that solar energy does not vary by more than a fraction of a percent over many years. However, measurements made by sophisticated radiometers aboard satellites suggest that the sun's energy output may vary considerably more than was thought. Moreover, the sun's energy output appears to change slightly with sunspot activity.

Sunspots are huge magnetic storms that show up as cooler (darker) regions on the suns surface. They occur in cycles, with the number and size reaching a maximum approximately every 11 years. During periods of maximum sunspots, the sun emits more energy (about 0.1 percent more) than during periods of sunspot minimums (see Figure 7). Evidently, the greater number of bright areas (*faculae*) around the sunspots radiate more energy, which offsets the effect of the dark spots.

Studies provide some evidence that changes in the *length* of the sunspot cycle (which ranges from 7 to 17 years) may have had an effect on global temperatures during the past century. Evidently, the shorter the sunspot cycle, the greater the energy output from the sun. In fact, one study of land temperatures over the Northern Hemisphere plotted from 1860 to 1985 reveals that air temperatures tended to be higher when the length of the sunspot cycle was shorter and that air temperatures tended to be lower when the length of the cycle was longer. Furthermore, shorter cycles also corresponded with a reduction in sea ice around Iceland.

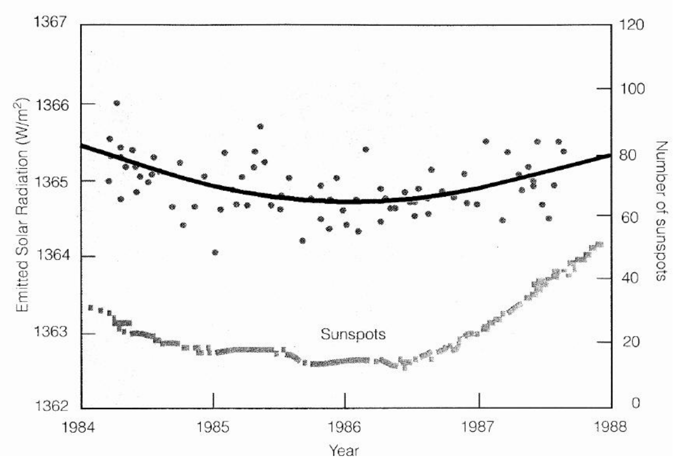

Figure 7: Changes in solar energy output (upper curve) in watts per square meter as measured by the Earth Radiation Budget Satellite. Bottom curve represents the yearly average number of sunspots. As sunspot activity increases from minimum to maximum, the sun's energy output increases by about 0.1 percent.