Carbon Dioxide and Climate

A current theory postulates that carbon dioxide regulates the temperature of the earth. This raises an interesting question: How do man’s activities influence the climate of the future?

by Gilbert N. Plass

The theories that explain worldwide climate change are almost as varied as the weather. The more familiar ones attribute changes of climate to Olympian forces that range from geological upheavals and dust-blanching volcanoes to long-term variations in the radiation of the sun and eccentricities in the orbit of the earth. Only the so-called carbon dioxide theory takes account of the possibility that human activities may have some effect on climate. This theory suggests that in the present century man is unwittingly raising the temperature of the earth by his industrial and agricultural activities.

Even the carbon dioxide theory is not new; the basic idea was first precisely stated in 1861 by the noted British physicist John Tyndall. He attributed climatic temperature-changes to variations in the amount of carbon dioxide in the atmosphere. According to the theory, carbon dioxide controls temperature because the carbon dioxide molecules in the air absorb infrared radiation. The carbon dioxide and other gases in the atmosphere are virtually transparent to the visible radiation that delivers the sun’s energy to the earth. But the earth in turn reradiates much of the energy in the invisible infrared region of the spectrum. This radiation is most intense at wavelengths very close to the principal absorption band (13 to 17 microns) of the carbon dioxide spectrum. When the carbon dioxide concentration is sufficiently high, even its weaker absorption bands become effective, and a greater amount of infrared radiation is absorbed [see illustration on next page]. Because the carbon dioxide blanket prevents its escape into space, the trapped radiation warms up the atmosphere.

A familiar instance of this “greenhouse” effect is the heating-up of a closed automobile when it stands for a while in the summer sun. Like the atmosphere, the car’s windows are transparent to the sun’s visible radiation, which warms the upholstery and metal inside the car; these materials in turn re-emit some of their heat as infrared radiation. Glass, like carbon dioxide, absorbs some of this radiation and thus traps the heat, and the temperature inside the car rises.

Water vapor and ozone, as well as carbon dioxide, have this effect because they too absorb energy in the infrared region. But the climatic effects due to carbon dioxide are almost entirely independent of the amount of these other two gases. For the most part their absorption bands occur in different regions of the spectrum. In addition, nearly all water vapor remains close to the ground, while carbon dioxide diffuses more evenly through the atmosphere. Thus throughout most of the atmosphere carbon dioxide is the main factor determining changes in the radiation flux.

The $2.3 \times 10^{15}$ (2.300 billion) tons of carbon dioxide in the earth’s present atmosphere constitute some .03 per cent of its total mass. The quantity of carbon dioxide in the atmosphere is determined by the amounts supplied and withdrawn from three other great reservoirs: oceans, rocks and living organisms. The oceans contain some $1.3 \times 10^{15}$ tons of carbon dioxide—about 30 times as much as the air. Some of the gas is dissolved in the water, but most of it is present in carbonate compounds. The oceans exchange about 200 billion tons of carbon dioxide with the atmosphere each year. When the equilibrium is disturbed, the oceans may engulf or disgorge billions of additional tons of carbon dioxide. This puts a damper on the fluctuations in the carbon dioxide content of the atmosphere: when the atmospheric concentration rises, the oceans tend to absorb much of the excess; when it falls, the oceanic reservoir replenishes it.

Both the atmosphere and the oceans continuously exchange carbon dioxide with rocks and with living organisms. They gain carbon dioxide from the volcanic activity that releases gases from the earth’s interior and from the respiration and decay of organisms; they lose carbon dioxide to the weathering of rock and the photosynthesis of plants. As these processes change pace, the content of carbon dioxide in the atmosphere also changes, shifting the radiation balance and raising or lowering the earth’s temperature.

Of course during any particular geologic era other factors may influence climate. Nonetheless let us examine some of the known facts of geological history and see how many can be ex-
plained in terms of variation in the carbon dioxide content of the atmosphere.

Studies of rock strata reveal that for the past billion years most of the world has had a tropical climate. Every 250 million years or so this tropical spell is broken by relatively short glacial periods which bury a substantial portion of the earth under ice sheets. These cool periods last several million years, during which the glaciers retreat and advance many times as the temperature rises and falls. During the last 620,000 years of the current glacial epoch, for example, deep ocean sediments show 10 distinct temperature cycles. The carbon dioxide theory may well account for these temperature fluctuations.

A decline in the carbon dioxide concentration in the atmosphere-ocean system—and a period of decline in worldwide temperature—may be induced by a number of developments. The rate of volcanic activity could slow down as the rate of rock weathering increased, or an especially flourishing mantle of vegetation could take up huge quantities of carbon dioxide and form new coal beds and other organic deposits in marshy areas. After a geologically short time, the adjustment of the atmosphere-ocean equilibrium to the leaner supply of carbon dioxide could bring the atmospheric concentration down to .015 per cent, half its present value. Calculations show that a 50-per-cent decrease in the amount of carbon dioxide in the air will lower the average temperature of the earth 3.9 degrees Fahrenheit.

We can be reasonably sure that such a sharp drop in temperature would cause glaciers to spread across the earth. As the ice sheets grow, the oceans shrink; at the height of glacial periods ice sheets contain 5 to 10 per cent of the oceans’ waters. The glaciers contain little carbon dioxide, however, because ice can hold very small amounts of carbonates compared to the same volume of sea water. The shrunken oceans thus accumulate an excess of carbon dioxide which they must release to the atmosphere in order to return to equilibrium. And so the cycle draws to a close: As carbon dioxide returns to the atmosphere, the earth’s temperature rises and the ice melts away. The oceans fill to their former levels, reabsorb the carbon dioxide they had released, and a new glacial epoch begins.

So long as the total amount of carbon dioxide in the atmosphere-ocean system does not change, such a cycle of temperature oscillation will tend to repeat itself. The period of the complete cycle would be determined primarily by the

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**INFRARED ABSORBERS** in the earth’s atmosphere include carbon dioxide (top) water vapor (center) and ozone (bottom). Spectral charts of their absorption in the infrared region show that these gases warm the earth by preventing its infrared radiation from escaping into space. Carbon dioxide influences climate because it has a broad absorption band at wavelengths (13 to 17 microns) near the wavelengths at which the earth’s infrared radiation is most intense. Water vapor and ozone can also influence climate.
time required for an ice sheet to form, grow to maximum size and melt away. Estimates indicate that this should take about 50,000 years, in agreement with the observed time for the cycle. Other time factors in the cycle, such as the period required for the ocean-atmosphere system to come to equilibrium after a change in its carbon dioxide concentration, are probably much shorter. The system never quite reaches equilibrium, however, because the freezing and melting of glaciers is out of phase with the fluctuation of carbon dioxide in the atmosphere. Glaciers are slow to form and slow to melt, so for thousands of years during the earth's recovery from an ice age the cold winds from melting glaciers continue to chill the earth.

The mechanism here proposed to explain the cycle of glaciation does not depend in any way upon the particular numbers assumed for illustrative purposes. Such oscillations will occur whenever the temperature during one phase of the cycle falls low enough to cause ice sheets to grow and during another phase rises high enough to cause them to melt. A change in the comparatively small volume of carbon dioxide in the atmosphere provides ample leeway to swing the temperature past either extreme. The oscillation is reinforced by the accompanying change in the earth's humidity. A colder atmosphere holds less water vapor, and so further reduces the atmospheric absorption of infrared radiation emitted by the earth's surface. At the same time, however, the earth's cloud cover thickens and precipitation increases despite the reduction in the water-vapor burden of the atmosphere. The top of a cloud is cooled by the radiation of heat into space; when there is less carbon dioxide in the atmosphere, cloud tops lose more heat energy and thus become colder. With a steeper temperature gradient there is increased convection within the cloud. The result is larger clouds and more precipitation. Moreover, since the cloud cover reflects the sun's visible radiation back into space, less solar energy reaches the earth, and the temperature falls still lower.

The geological record indicates that the huge capacity of the biosphere to store and turn over carbon dioxide has also had its effect upon climatic change. We know that plants borrow 60 billion tons of carbon dioxide yearly for photosynthesis. Under present conditions the organic world repays nearly all of this debt each year via respiration and decay. The formation of new fossil fuel.
deposits withholds at most only 100 million tons of carbon dioxide, or less than .2 per cent of the annual amount used for photosynthesis. At one time, however, the withdraws were much larger. During the Carboniferous period, when most of the coal and oil deposits were formed, about $10^{14}$ tons of carbon dioxide were withdrawn from the atmosphere-ocean system. This staggering loss must have dropped the earth's temperature to chilly levels indeed; it is not surprising that the gigantic glaciers that moved across the earth after this period were perhaps the most extensive in history.

The present capacity of plants to consume carbon dioxide in photosynthesis gives us an interesting clue to the carbon dioxide content of the atmosphere in bygone ages. Plants are almost perfectly adapted to the spectral range and intensity of the light they receive, yet they grow far more rapidly and luxuriantly in an atmosphere that contains five to 10 times the present carbon dioxide concentration; in fact, florists sometimes release tankfuls of carbon dioxide in greenhouses to promote plant growth. The present carbon dioxide concentration in the atmosphere must therefore be unusually low. Apparently plant evolution was keyed to some much higher concentration in the atmosphere of the geologic past. This hypothesis is also supported by the known fact that the earth's climate was warmer during most of geologic time; presumably the atmosphere then contained a much higher percentage of carbon dioxide.

Much of the carbon dioxide in the atmospheres of past geologic epochs now lies buried in the carbon dioxide reservoir of the earth itself. The earth's hot springs and volcanoes pour about 100 million tons of carbon dioxide back into the atmosphere per year. The earth in turn recaptures approximately the same amount each year by the weathering of rocks. But this equilibrium is upset during periods of mountain-building. In fact, the carbon dioxide theory provides an essential link to explain the timing of the last two glacial epochs with respect to the mountain-building periods that preceded them.

At least several million years intervened between the climax of these mountain-building episodes and the formation of the great ice sheets. If glaciation was brought on only by the elevation of the land or by the slight darkening of the sky with the dust of volcanoes, there should have been no

**CARBON DIOXIDE BALANCE** results from the equilibrium of natural processes that continuously increase and decrease the atmospheric carbon dioxide concentration. The numbers in parentheses after the name of a process indicate the number of tens of carbon
dioxide being used in that process each year. Vast quantities of carbon dioxide are stored in the three great natural reservoirs: the earth, the oceans and the biosphere. These reservoirs can absorb carbon dioxide or release it to the atmosphere, depending on equilibrium conditions. The black arrows indicate the artificial processes by which man adds carbon dioxide to the atmosphere.
ATMOSPHERE-OCEAN SYSTEM will change the surface temperature of the earth if its equilibrium is disrupted. The three curves here show how this equilibrium shifts when the oceans contain 100 per cent (solid line), 95 per cent (broken line) and 90 per cent (dotted line) of their present volume of water. If the total carbon dioxide content of the system drops only 7 per cent, the equilibrium shifts from point A, its present value, to point B. Such a change would cut the atmospheric carbon dioxide pressure to half its present value, bringing on a possible glacial epoch. As the glaciers grow, the oceans shrink; at the height of a glacial period the ice sheets contain from 5 to 10 per cent of the oceans’ waters. With the oceans reduced to 95 per cent of their present volume, the equilibrium would shift to point C, because the shrunken oceans would be forced to release some of their carbon dioxide to the air. Then the temperature rises, glaciers melt and the cycle begins anew.

great time lag before the onset of the glaciers. But these upheavals exposed large quantities of igneous rock to the chemical action of the minute amounts of atmospheric carbon dioxide dissolved in the rain water that washed over them. Over millions of years the weathering of the rock trapped vast quantities of carbon dioxide from the air. With the atmospheric concentration reduced sufficiently, the temperature fell, permitting the young mountains to provide natural birthplaces for the glaciers that then crept across the earth.

Some periods of mountain-building have not produced glaciers. In these periods the output of carbon dioxide from volcanoes, which are especially active during the early stages of mountain-building, might have balanced the carbonatic consumption of the newly exposed rocks. In fact, a landscape teeming with active volcanoes could easily release more carbon dioxide than the rocks could possibly absorb, so the temperature of the earth would rise sufficiently to prevent the expansion of glaciers.

The geological effects of volcanic action, coal formation or any other local disturbance of the carbon dioxide concentration are not restricted to the area in which they occur. If the amount of carbon dioxide in one hemisphere of the earth rises or falls sharply, the concentration in the other hemisphere changes rather quickly. In less than a few decades the concentration in both hemispheres becomes identical. According to the carbon dioxide theory, this rapid diffusion helps to explain the fact that glaciers advance and retreat simultaneously in both hemispheres.

During the past century a new geological force has begun to exert its effect upon the carbon dioxide equilibrium of the earth. By burning fossil fuels man dumps approximately six billion tons of carbon dioxide into the atmosphere each year. His agricultural activities release two billion tons more. Grain fields and pastures store much smaller quantities of carbon dioxide than the forests they replace, and the cultivation of the soil permits the vast quantities of carbon dioxide produced by bacteria to escape into the air.

Not all of this eight billion tons of surplus carbon dioxide remains in the atmosphere. Plants remove some of it. When the atmospheric concentration rises, plants use more carbon dioxide for photosynthesis. In a few years, however, the increase in the rate of photosynthesis is balanced by advances in the rate of respiration and decay processes. The net result is only a slight increase in the carbon dioxide content of the biosphere.

Most of the carbon dioxide added to the atmosphere by human activities will ultimately be absorbed by the oceans. To predict the effect of human activities upon climate we must calculate just how rapidly this happens. Recent studies make it appear that the volume of carbon dioxide dissolved in the oceans comes to equilibrium with the carbon dioxide pressure of the atmosphere in about 1,000 years, and that the oceans take up about half of any carbon dioxide added to the air. Over a longer period of time, perhaps several thousand years, the oceans take up much larger additional quantities of carbon dioxide in carbonate compounds before the system again reaches equilibrium. These equilibrium rates are quite significant, because they will govern the temperature of the earth as long as man burns large amounts of fossil fuels.

We have only to extrapolate existing records of temperature and fossil-fuel consumption to predict the climate of the future. Quite accurate records of the amount of fossil fuel consumed in the world each year show that in the past 100 years man has added about 360 billion tons of carbon dioxide to the atmosphere. As a result the atmospheric concentration has increased by about 13 per cent. The carbon dioxide theory predicts that such an increase should raise the average temperature of the earth one degree F. This is almost exactly the average increase recorded all over the world during the past century! If fuel consumption continues to increase at the present rate, we will have sent more than a trillion tons of carbon dioxide into the air by the year 2000. This should raise the earth’s average temperature 3.6 degrees.

In less than 1,000 years, if consumption continues to increase at the current
rate, we will have exhausted the counter presently known reserves of coal and oil. By that time we will have multiplied the carbon dioxide tonnage of the air 18 times. When the ocean-atmosphere system comes back to equilibrium, the concentration of carbon dioxide in the air will be 10 times greater than it is today, and the earth will be 22 degrees warmer. In another few thousand years, when the carbonate content of the oceans has reached equilibrium, the concentration will still be four times greater than it is today. The earth's temperature will then fall to about 12.5 degrees above its present average.

Meanwhile the carbon dioxide content of the oceans will have doubled. This raises an incidental question about the welfare of sea organisms. We know that an increase in carbon dioxide concentration increases the acidity of water, and that many marine animals are extremely sensitive to changes in acidity. However, if the carbon dioxide content of the air were to increase sevenfold, the acidity (pH) of sea water would not rise more than .5 above its present value. Thus changes in carbon dioxide concentration, which have such a profound effect on climate, will probably not disturb future marine life. Perhaps only man will be uncomfortable.

We shall be able to test the carbon dioxide theory against other theories of climatic change quite conclusively during the next half-century. Since we now can measure the sun's energy output independent of the distorting influence of the atmosphere, we shall see whether the earth's temperature trend correlates with measured fluctuations in solar radiation. If volcanic dust is the more important factor, then we may observe the earth's temperature following fluctuations in the number of large volcanic eruptions. But if carbon dioxide is the most important factor, long-term temperature records will rise continuously as long as man consumes the earth's reserves of fossil fuels.

MAN UPSETS THE BALANCE of natural processes by adding billions of tons of carbon dioxide to the atmosphere each year. Most of this carbon dioxide is released by the burning of fossil fuels in homes and factories, such as these plants in Youngstown, Ohio. Like the smoke in the photograph, the carbon dioxide released in this manner diffuses rapidly throughout the atmosphere.