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FEATURE ARTICLE

Carbon Dioxide and the Climate

A 1956 *American Scientist* article explores climate change; two contemporary commentaries illuminate its relevance to the present

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Scientists have long been fascinated with the problem of explaining variations in the climate. For at least nine-tenths of the time since the beginning of recorded geological history, the average temperature of the Earth has been higher than it is today. Between these warm epochs there have been severe periods of glaciation which have lasted a few million years and which have occurred at intervals of roughly 250,000,000 years. Of more immediate interest to us is the general warming of the climate that has taken place in the last sixty years.

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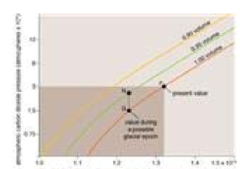
Theories of climatic change are exceedingly numerous. Is it possible that any of these theories can explain most of the known facts about climate? The most widely held theories at the present time call upon variations in the solar energy received by the earth, changes in the amount of volcanic dust in the atmosphere, and variations in the average elevation of the continents. Although it is entirely possible that changes in each of these factors may have had an influence on the Earth's climate at particular times and places, none of these theories alone seems able to explain a majority of the known facts about world-wide climatic variations.

Although the carbon dioxide theory of climatic change was one of the most widely held fifty years ago, in recent years it has had relatively few adherents. However, recent research work suggests that the usual reasons for rejecting this theory are not valid. Thus it seems appropriate to reconsider the question of variations in the amount of carbon dioxide in the atmosphere and whether it can satisfactorily account for many of the world-wide climatic changes.

Because of the relatively low temperatures at the Earth's surface and in the atmosphere, virtually all of the outgoing radiation from the Earth to space is in the infrared region of the spectrum. Thus it is important to know which constituents of the atmosphere absorb in the infrared. The three most abundant gases in our atmosphere are oxygen, nitrogen, and argon. However, none of these three gases absorb appreciably in the relevant spectral region in the infrared. If these were the only gases in our atmosphere, our climate would be considerably colder than it is today. The heat radiated from the surface of the Earth would not be stopped in its passage out to space with the result that the Earth's surface would cool rapidly.

Fortunately for us, three other gases occur in our atmosphere in relatively minute quantities: carbon dioxide, water vapor, and ozone. Unlike the more abundant gases, all three of these rarer gases absorb strongly over at least a portion of the infrared spectrum. The concentration of carbon dioxide in the atmosphere is about 0.03 per cent by volume, it is fairly uniformly mixed as high as accurate measurements have been made. Water vapor and ozone also exist in very small concentrations in the atmosphere, but the exact amount that is present varies with time and place.



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The infrared absorption properties of carbon dioxide, water vapor, and ozone determine our climate to a large extent. Their action has often been compared to that of a greenhouse. There the rays of the sun bring the heat energy in through the transparent glass. However, the outgoing heat energy from the plants and other objects in the greenhouse is in the infrared where glass is largely opaque. The heat energy is fairly effectively trapped inside the greenhouse and the temperature is considerably warmer than outside.

In a similar manner the temperature at the surface of the Earth is controlled by the transparency of the atmosphere in the visible and infrared portions of the spectrum. The incoming radiation from the sun in the visible portion of the spectrum reaches the surface of the Earth on a clear day with relatively little attenuation since the atmosphere is transparent to most frequencies in the visible. However, in order to have a warm climate, this heat energy must be held near the surface of the Earth and cannot be reradiated to space immediately. The atmosphere is opaque or partially opaque to a large range of frequencies in the infrared because of the absorption properties of the three relatively rare gases described above. Thus radiation emitted by the Earth's surface cannot escape freely to space and the temperature at the surface is higher than it would be otherwise. The atmosphere has just the same properties as the glass in the greenhouse. The carbon dioxide theory states that, as the amount of carbon dioxide increases, the atmosphere becomes opaque over a larger frequency interval; the outgoing radiation is trapped more effectively near the Earth's surface and the temperature rises. The latest calculations show that if the carbon dioxide content of the atmosphere should double, the surface temperature would rise 3.6 degrees Celsius and if the amount should be cut in half, the surface temperature would fall 3.8 degrees.

The carbon dioxide theory was first proposed in 1861 by Tyndall. The first extensive calculations were necessarily done by very approximate methods. There are thousands of spectral lines due to carbon dioxide which are responsible for the absorption and each of these lines occurs in a complicated pattern with variations in intensity and the width of the spectral lines. Further the pattern is not even the same at all heights in the atmosphere, since the width and intensity of the spectral lines varies with the temperature and pressure. Only recently has a reasonably accurate solution to the problem of the influence of carbon dioxide on surface temperature been possible, because of accurate infrared measurements, theoretical developments, and the availability of a high-speed electronic computer.

The fact that water vapor absorbs to some extent in the same spectral interval as carbon dioxide is the basis for the usual objection to the carbon dioxide theory. According to this argument the water vapor absorption is so large that there would be virtually no change in the outgoing radiation if the carbon dioxide concentration should change. However, this conclusion was based on early, very approximate treatments of the very complex problem of the calculation of the infrared flux in the atmosphere. Recent and more accurate calculations that take into account the detailed structure of the spectra of these two gases show that they are relatively independent of one another in their influence on the infrared absorption. There are two main reasons for this result: (1) there is no correlation between the frequencies of the spectral lines for carbon dioxide and water vapor and so the lines do not often overlap because of nearly coincident positions for the spectral lines; (2) the fractional concentration of water vapor falls off very rapidly with height whereas carbon dioxide is nearly uniformly distributed. Because of this last fact, even if the water vapor absorption were larger than that of carbon dioxide in a certain spectral interval at the surface of the Earth, at only a short distance above the ground the carbon dioxide absorption would be considerably larger than that of the water vapor. Careful estimates show that the temperature changes given above for carbon dioxide would not be reduced by more than 20 per cent because of water vapor absorption.

One further objection has been raised to the carbon dioxide theory: the atmosphere is completely opaque at the center of the carbon dioxide band and therefore there is no change in the absorption as the carbon dioxide amount varies. This is entirely true for a spectral interval about one micron wide on either side of the center of the carbon dioxide band. However, the argument neglects the hundreds of spectral lines from carbon dioxide that are outside this interval of complete absorption. The change in absorption for a given variation in carbon dioxide amount is greatest for a spectral interval that is only partially opaque; the temperature variation at the surface of the Earth is determined by the change in absorption of such intervals.

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Thus there does not seem to be a fundamental objection to the carbon dioxide theory of climate change. Further the temperature changes given by the theory for reasonable variations in the carbon dioxide amount are more than enough to cause noticeable changes in the climate. It is not usually appreciated that very small changes in the average temperature can have an appreciable influence on the climate. For example, various authorities estimate that, if the average temperature should decrease from 1.5 to 8 degrees, the glaciers would again form over an appreciable fraction of the Earth's surface. Similarly a rise in the average temperature of perhaps only 4 degrees would bring a tropical climate to most of the Earth's surface.

Before discussing in detail the carbon dioxide theory of climatic change it is first necessary to study the various factors that enter into the carbon dioxide balance, including the exchange of carbon dioxide between the oceans and the atmosphere.

The largest loss of carbon dioxide from the atmosphere is due to the process of photosynthesis which uses about 60 x 10^9 tons per year. In a steady state precisely the same amount of carbon dioxide is returned to the atmosphere each year by all the processes of respiration and decay of plants and animals, provided only that none is permanently lost in the form of new coal, oil, and other organic deposits. At the present time, at least, this loss is very small (0.01 x 10^9 tons per year) and can be neglected for all practical purposes. If this steady state of absorption and emission of carbon dioxide by the organic world is disturbed, for example, by a sudden increase of carbon dioxide in the atmosphere, it is known that the amount used in photosynthesis would then increase. However, after a very few years the processes of decay and respiration would also have increased. Since an average carbon atom that has been used in photosynthesis returns to the atmosphere from the biosphere within about 10 years, and virtually all of the carbon atoms return within 250 years it follows that the factors influencing the carbon dioxide balance from the organic world would again be in balance in a very few years.

The two most important contributing factors from the inorganic world are the release of carbon dioxide from the interior of the Earth by hot springs, volcanoes, and other sources and the formation of carbonates in the weathering of igneous rocks. They happen to be nearly in balance today. The first one adds and the second subtracts about 0.1 x 10^9 tons per year to the atmosphere. Thus it appears that as far as natural factors are concerned, the amount of carbon dioxide taken out of the atmosphere is very nearly equal to the amount returned to it. The specific numbers given in this section are only order of magnitude estimates. The values given here are averages of some of the more careful estimates.

Recently, however, man has added an important new factor to the carbon dioxide balance. As first pointed out by Callendar, the combustion of fossil fuels is adding 6.0 x 10^9 tons per year of carbon dioxide to the atmosphere at the present time and the rate is increasing every year. Today this factor is larger than any contribution from the inorganic world. Thus today man by his own activities is increasing the carbon dioxide in the atmosphere at the rate of 30 per cent a century. The possible influence of this on the climate will be discussed later.

The oceans contain a vast reservoir of carbon dioxide; some of it is in the form of dissolved gas, but it consists mostly of carbonates in various degrees of ionization. From the known dissociation constants for sea water, it is possible to calculate the atmospheric carbon dioxide pressure that is in equilibrium with a given amount of carbonates in the oceans. At the present time the carbon dioxide pressure is about 3 x 10^{-4} atmospheres; there are 2.3 x 10^{12} tons of carbon dioxide in the atmosphere and 130 x 10^{12} tons of carbon dioxide and carbonates in the oceans. Thus the oceans contain over fifty times as much carbon dioxide as the atmosphere. If conditions should change, the oceans can add to or subtract from the amount in the atmosphere.

Kulp has recently shown from radiocarbon determination that the deep ocean waters at the latitude of Newfoundland were at the surface 1,700 years ago. This suggests that it may take tens of thousands of years for the waters of the deep ocean to make one complete circuit from the surface to the bottom and back. Only the surface waters of the oceans can absorb carbon dioxide directly from the atmosphere. Since there is very little circulation between the surface waters and the ocean depths, the time for the atmosphere-ocean system to return to equilibrium following a disturbance of some sort is at least as long as the turnover time of the oceans. Thus, if the atmospheric carbon dioxide amount should suddenly increase, it may easily take a period of tens of thousands of years before the atmosphere-ocean system is again in equilibrium.

Let us next examine some of the variations in the atmospheric carbon dioxide amount in past geological epochs and their correlation with the climate as deduced from the geologic record. It is interesting that a large number of these climatic variations can be explained simply and naturally by the carbon dioxide theory.

During the last glacial epoch of perhaps a million years' duration, four distinct periods of glaciation separated by warmer interglacial periods have long been recognized. Recently Wiseman has studied the sediments of the deep ocean floor and has found evidence for ten distinct temperature minima with the last 620,000 years. It appears that a fundamental property of a glacial epoch is to have a climate that is continually fluctuating. The glaciers advance and then recede and repeat the cycle several times before the end of the glacial epoch. No other theory of climatic change seems able to explain in a simple and straightforward manner these continual oscillations in climate during a million-year epoch of glaciation.

In order to understand these oscillations let us consider the figure where the equilibrium pressure of the carbon dioxide in the atmosphere is plotted against the total amount of carbon dioxide in the atmosphere-ocean system. These curves were calculated as described above with the additional assumption that the average temperature varies as predicted by the carbon dioxide theory. Curves are shown when the oceans have 0.90, 0.95, and 1.00 times their present volume in order to allow for the face that the ocean volume decreases during a period of glaciation.

The present value for the carbon dioxide pressure (3 x 10^{-4} atmosphere) and the total amount of carbon dioxide in the atmosphere-ocean system (1.32 x 10^{14} tons) is marked with the letter "P" in the figure. Let us suppose that a million years ago the carbon dioxide balance was upset and that the total amount of carbon dioxide in the atmosphere-ocean system was reduced 7 per cent to 1.23 x 10^{14} and that it remained fixed at this new lower value throughout the ensuing glacial period. Let us further assume that if the average temperature should fall 3.8 degrees that great ice sheets would again form and cover sizable portions of the continents. With the reduced carbon dioxide amount the atmosphere-ocean system would finally come to equilibrium at the point "G" in the figure. The new atmospheric carbon dioxide pressure would be 1.5 x 10^{-4} atmosphere. This would reduce the temperature by 3.8 degrees according to this theory; this would be sufficient to start a period of glaciation.

Let us assume in agreement with the estimates of glacial authorities that the glaciers contain about 5 per cent of the water of the oceans when the ice sheets have reached their maximum development. Since only small amounts of carbonates are held permanently in glacial ice, the loss of this water by the oceans means that oceans now contain too much carbonate for their reduced volume. They release that carbon dioxide, thus increasing the amount in the atmosphere.

The atmosphere-ocean system again reaches equilibrium at the point "N" of the figure some tens of thousands of years later. This point represents the equilibrium conditions when the ocean volume is 95 per cent of its present value and the atmospheric carbon dioxide pressure is 2.5 x 10^{-4} atmosphere. However, when the carbon dioxide pressure reaches this value, the average surface temperature rises to virtually its present value. It is then too warm to maintain the glaciers and they start to melt. This process probably takes thousands of years, but finally the oceans return to their original volume. Now the oceans do not contain sufficient carbonates for their increased volume; the atmosphere-ocean system is no longer in equilibrium. The oceans absorb additional carbon dioxide from the atmosphere until after tens of thousands of years the system is again near equilibrium at the point "G" in the figure. This cycle continues indefinitely as along as the total carbon dioxide amount in the atmosphere-ocean system remains fixed at 1.23 x 10^{14} tons. The period for one complete cycle depends on the rate of circulation of the oceans, but may be very roughly estimated as 50,000 years or more.

The climate must continually oscillate from a glacial to an interglacial period until the total carbon dioxide amount is again increased by a change in one of the factors in the carbon dioxide balance. When the total carbon dioxide amount is reduce slightly below its present value, there is no stable state for the climate; it must continually oscillate. On the other hand, if some event should greatly reduce the total carbon dioxide amount (perhaps by 30 per cent or more), a permanent period of glaciations without these oscillations would be possible. In order to explain the various states in this cycle more clearly, specific numbers have been assumed. However, it may be verified easily that none of the conclusions that have been reached depend in a critical way on the particular numbers that were chosen. It should also be pointed out that, if there is sufficient time in the various stages of the cycle for the oceans to come to equilibrium with calcium carbonate, the form of the curves in the figure is somewhat changed, but none of the conclusions reached above is essentially altered.

In addition to lower temperatures, increased precipitation is also necessary for the formation of extensive glaciation. Most theories of climatic change have found it very difficult to explain this increased precipitation. For example, in the variable sun theory, a decrease in the sun's radiation reduces the surface temperature. However, this also reduces the energy available to drive the general circulation of the atmosphere. A decreased circulation presumably means decreased cloud formation and precipitation. In order to account for the increased precipitation an ingenious, but unconvincing modification of the variable sun theory states that glacial periods result from an increase in the sun's radiations. The slightly increased average temperatures are supposed to be compensated by the greater precipitation.

The carbon dioxide theory provides a simple, straight-forward explanation for the increased precipitation during a glacial epoch. One of the parameters that determines the amount of precipitation from a given cloud is the radiant loss of heat energy from the upper surface of the cloud. If this radiation loss increases, the temperature at the upper surface of the cloud decreases. This increases the temperature difference between the upper and lower surface of the cloud. Because of these more vigorous convection currents, it is more likely that rain will fall from the cloud. Thus on the average there is more rainfall from a given cloud if the radiation loss from its upper surface increases.

According to the carbon dioxide theory there is a smaller than normal amount of carbon dioxide in the atmosphere when glaciers are beginning to form. Not only the surface of the Earth, but also the upper surface of a cloud is cooler, since they can lose heat energy more rapidly to space. Recent calculations show that the upper surface of a cloud at a height of 4 kilometers is 2.2 degrees cooler when the carbon dioxide pressure is half the present value. Further the upward flux of radiation that strikes the lower surface of the cloud is larger when the carbon dioxide amount is reduced; thus the lower surface of the cloud is warmer than before. Thus, the larger temperature difference between the upper and lower surfaces of the cloud causes increased convection in the cloud; the level of precipitation should increase appreciably. Thus, according to the carbon dioxide theory, colder and wetter climates occur together.

There is considerable geological evidence that extensive outbursts of mountain building occurred several millions of year before each of the last two major glacial epochs. Again the carbon dioxide theory seems to be the only theory that suggests a reason for the time lag between these two events. During a major period of mountain building, tremendous quantities of igneous rock are exposed to weathering. In mountainous country the zone for the active disintegration of rock extends much farther beneath the surface than it does in flat country. The weathering of igneous rock changes it into carbonates, thus removing carbon dioxide from the atmosphere.

The explanation of the time lag in terms of the carbon dioxide theory is that large quantities of carbon dioxide are removed from the atmosphere by the increased weathering after a period of major mountain building. After some millions of years, the carbon dioxide content of the atmosphere is reduced sufficiently to bring on a period of glaciation. From estimates of the increased weathering that occurs after the uplift of a mountain range, it is found that the time lag is of the order of a million years.

However, during an epoch of mountain building greatly increased amounts of carbon dioxide must be released from the interior of the Earth into the atmosphere through volcanic vents and hot springs. Additional millions of years are required to use up this additional carbon dioxide by the process of weathering. Thus the actual time interval between the onset of an epoch of mountain building and the ensuing glaciation can be considerably greater than a million years, if large additional quantities of carbon dioxide are released from the interior of the Earth. Indeed, if these amounts are very large, weathering would be unable to reduce the atmospheric carbon dioxide content to a sufficiently low level to cause a glacial period. In fact some periods of mountain building have not been followed by extensive glaciation. Such theories of glacial change as the variation in the amount of volcanic dust in the atmosphere and the change in the average elevation of the lands have found it difficult to explain why the glaciers do not form immediately after the uplift of a major mountain range.

During the geological history of the Earth the amount of carbon dioxide lost from the atmosphere in the formation of coal, oil, and other organic deposits has varied widely. This loss is relatively minor today. On the other hand it would be especially large during a period such as the Carboniferous when there were extensive marshes and shallow seas. At the end of the Carboniferous the atmospheric carbon dioxide content may have been reduced to a very low level because of the tremendous quantities that had been used in the newly formed coal and oil deposits. It is perhaps significant that the glaciation at the end of the Carboniferous may have been the most severe in the Earth's history.

Radiocarbon dating indicates that recent changes in climate have been contemporaneous in both hemispheres. In the last fifty years virtually all known glaciers in both hemispheres have been retreating. According to the carbon dioxide theory, such changes in climate should occur at the same time in both hemispheres. The exchange of air between the two hemispheres is relatively rapid. Even if the atmospheric carbon dioxide content should increase suddenly in one hemisphere through a variation of some factor that enters into the carbon dioxide balance, the amount in the two hemispheres should again be equal in a relatively short interval on the geological time scale, perhaps no more than a few decades. It should be mentioned that it is possible to have glaciation in one hemisphere and not the other even though the atmospheric carbon dioxide amounts are the same. If one hemisphere has extensive mountain ranges and the other is relatively flat, glaciers could spread from the mountainous region of one hemisphere whereas they would be unable to form on the more level land of the hemisphere at the same average temperature.

The carbon dioxide theory has given plausible explanations for the beginning of a glacial period and of the climatic oscillations that occur during a glacial period. What increases the total carbon dioxide amount sufficiently to bring a glacial period to an end? One possibility is that the rock weathering is slowly reduced because of the increasing flatness of the land. In addition extensive glaciation probably reduces the rate of weathering for the fraction of the land surface that is covered by the glaciers. Thus, as the loss of carbon dioxide from the atmosphere for weathering decreases as a glacial epoch nears its end, the amount of atmospheric carbon dioxide slowly increases until finally the surface temperature is too high to allow further growth of the glaciers. An extensive period of mountain building has occurred at intervals of roughly 250,000,000 years during the Earth's history and a glacial period has followed in each case during the time interval when sufficient carbon dioxide was removed from the atmosphere.

What is the reason for the recent temperature rise that is found throughout the world? Will this trend toward warmer climates continue for some time? The carbon dioxide theory may provide the answer. We have discussed the burning of fossil fuels which is adding more than 6 x 10^{9} tons per year of carbon dioxide to the atmosphere. If all of this extra carbon dioxide remains in the atmosphere, the average temperature is increasing at the rate of 1.1 degrees per century from this cause. Since 1900 a careful study of world temperature records shows that the average temperature has been increasing at roughly this rate. Of course, the agreement between these two numbers could be merely a coincidence.

As the concentration of carbon dioxide in the atmosphere increases, there are two factors in the carbon dioxide balance than can change. First the oceans absorb more carbon dioxide to come to equilibrium with the larger atmospheric concentration. However, only the surface waters can absorb this gas and because of the slow circulation of the oceans, it probably takes at least ten thousand years for this process to come to equilibrium. Whenever the carbon dioxide amount is increasing an upper limit for the amount absorbed by the oceans can be found at any time by assuming the atmosphere-ocean system is always in equilibrium. The actual amount absorbed by the oceans will be considerably less than the amount calculated in this manner for at least several centuries after a sudden increase in the atmospheric carbon dioxide amount. In the first few centuries the surface ocean waters can absorb only a relatively small fraction of the additional carbon dioxide.

The second factor that can change is the amount used in photosynthesis. A higher level of photosynthetic activity can be supported by the increased carbon dioxide amount. As previously discussed, this process temporarily withdraws some of the additional carbon dioxide from the atmosphere into the organic world. However, in a relatively few years the increased rates of respiration and decay bring this process back into equilibrium and only a relatively small amount of carbon dioxide is permanently lost from the atmosphere. Thus it appears that a major fraction of the additional carbon dioxide that is released into the atmosphere remains there for at least several centuries.

Even if there may be some question as to whether or not the general amelioration of the climate in the last fifty years has really been caused by increased industrial activity, there can be no doubt that this will become an increasingly serious problem as the level of industrial activity increases. In a few centuries the amount of carbon dioxide released into the atmosphere will have become so large that it will have a profound influence on our climate.

After making allowance for industrial growth, a conservative estimate shows that the known reserves of coal and oil will be used up in about 1,000 years. If this occurs, nearly 4×10^{13} tons of carbon dioxide will have been added to the atmosphere; this is seventeen times the present amount. The total amount in the atmosphere-ocean system will have increased from 1.32×10^{14} tons to 1.72×10^{14} tons. Even if the atmosphere-ocean system is assumed to be in equilibrium at the end of the thousand year period, the atmospheric carbon dioxide pressure will be 3×10^{-3} atmospheres, which is 10 times the present value; the corresponding increase in the temperature from this cause will be 13.4 degrees. If it is further assumed that there would be sufficient time for the calcium carbonate to dissolve and come to equilibrium in the oceans, the atmospheric pressure will be 1.1×10^{-3} atmospheres and the temperature rise 7.0 degrees. The last figure is a lower limit for the temperature rise that will occur because of man's industrial activities; the actual temperature rise must be larger since there will be insufficient time for these various equilibria to be established. Our energy requirements are increasing so rapidly that the use of nuclear fuels will probably not change materially the rate of use of the organic fuels.

Unfortunately it is difficult to obtain any direct evidence for the carbon dioxide content of the atmosphere during past geological epochs. In fact it is not even certain from direct measurements whether or not the carbon dioxide content has increased in the last 50 years. A plot of such measurements can be fitted nicely with a linear curve that increases by 10 per cent in that time interval. However, the probable error for most of the measurements is so large that this result is not very firmly established. Because of its importance to the climate, regular measurements of the atmospheric carbon dioxide content should be started at several different country locations and continued for a number of decades. Since the atmospheric carbon dioxide content varies somewhat with the past history of the air mass and the time of year, a number of measurements are necessary in order to obtain a reliable average. The present predicted rise of 3 per cent a decade could be easily observed with the present techniques of analysis. As to the carbon dioxide content of the atmosphere at earlier periods, only general discussions of the various factors that affect the carbon dioxide balance can be given at the present time. It is possible though that we will be able to calculate the carbon dioxide amount of a past epoch from measurements of the ocean temperature and the rate of carbonate deposition during that epoch together with further studies of the atmosphere-ocean equilibrium.

There is some interesting evidence which suggests that the carbon dioxide content of the atmosphere was once much larger than at present. It is known that plants grow more luxuriantly and rapidly in an atmosphere that has from five to ten times the normal carbon dioxide amount. In fact carbon dioxide is sometimes released in greenhouses in order to promote growth. Since plants are perfectly adapted to make maximum use of the spectral range and intensity of the light that reaches them from the sun for photosynthesis, it seems strange that they are not better adapted to the present carbon dioxide concentration in the atmosphere. The simplest explanation of this fact is that the plants evolved at a time when the carbon dioxide concentration was considerably higher than it is today and that it has been at a higher level during most of the ensuing time. Higher temperatures than today during most of the Earth's history would have resulted from this higher carbon dioxide content. In fact the geological evidence shows that warmer climates than today have existed for at least nine-tenths of the time since the Cambrian period.

Further evidence as to the carbon dioxide amounts in the past is provided by the pH of sea water. There is a definite pH value associated with a given atmospheric carbon dioxide amount when the atmosphere-ocean system is in equilibrium. Further, many marine animals are very sensitive to the pH value, the higher marine animals being more sensitive in general than the lower. For example, herring are killed if the pH changes by more than one-half unit; lower marine animals such as sea urchins, diatoms, and algae cannot tolerate pH changes of more than one unit.

This suggests that the pH of the oceans has not varied by more than these amounts since the time when these animals evolved or at most that the pH has changed extremely slowly so that these animals could evolve to live in the changed environment. However, even with the stringent requirement that the pH of sea water should not change by more than one-half unit, the atmospheric carbon dioxide amount can still vary by a factor of fifty and maintain equilibrium between the atmosphere and the oceans. Thus very large changes in the atmospheric carbon dioxide amount can occur without influencing either marine or land animals; still larger variations would even be possible over time intervals sufficiently long to allow the animals to adapt to their new environment.

All calculations of radiocarbon dates have been made on the assumption that the amount of atmospheric carbon dioxide has remained constant. If the theory presented here of carbon dioxide variations in the atmosphere is correct, then the reduced carbon dioxide amount at the time of the last glaciation means that all radiocarbon dates for events before the recession of the glaciers are in question.

Variations in the concentration or distribution of any gas that absorbs in the infrared portion of the spectrum can influence the surface temperature in the same manner as we have already discussed for carbon dioxide. Ozone and water vapor are the only two other gases that absorb in this region and also exist in the atmosphere in sufficient quantities to have an appreciable effect. Few suggestions have been made that relate variations in the concentration of these two gases to the climate, since these changes do not seem to be related directly to definite geological factors. However, recent calculations have shown that variations in the distribution of ozone can appreciably change the surface temperature. Normally the ozone concentration has a maximum in the stratosphere with relatively small amounts at lower altitudes. Vertical air currents occasionally bring some of the ozone down from the stratosphere, thus greatly increasing the concentration at lower altitudes. This is sufficient to increase the surface temperature from radiation effect by several degrees.

The relative humidity as a function of altitude is continually changing and a similar effect on the surface temperature exists for water vapor. These relatively rapid variations in temperature are superimposed on those from carbon dioxide alone. The latter variations are relatively constant over long time intervals compared to the former. However, water vapor can also have an effect over long time intervals, since the amount that can be held in the atmosphere decreases very rapidly as the temperature drops. During a glacial period the atmosphere has a smaller capacity to hold water vapor; for this reason the infrared heat energy from the Earths surface can escape more easily to space. Thus the influence of water vapor on the infrared absorption tends to reduce the surface temperature still more once a glacial period has started. The increased cloud amount during such a period also acts to reduce the surface temperature by reflecting the incoming solar radiation back to space. Therefore the temperature decrease during a glacial epoch is probably somewhat greater than is calculated from the carbon dioxide effect alone.

A very large number of different theories of climatic change has been proposed. As more evidence about past climatic change is obtained, each theory has to meet continually more rigorous tests in order to explain the known facts. Each of the major theories of climatic change predicts a different temperature trend during the remainder of this century. A comparison of these predictions with the actual record at the end of the century will provide an important test of these theories.

The variable sun theory predicts that the temperature will decrease for some decades. The maximum of the 80-year period in the sunspot cycle probably occurred in 1947. Thus the total energy received from the sun including the ultraviolet should decrease for some decades when the records are averaged over the shorter periods in the cycle. On the other hand a continued increase in the average temperature could be justified by the variable sun theory only if measurement showed a corresponding increase in the solar constant.

Changes in the average elevation of the continents clearly cannot be used to explain any variations in the climate over a period of a few centuries. However, the volcanic dust theory predicts appreciably lower temperatures for a few years following volcanic activity that throws large quantities of dust into the atmosphere. The last such explosion was when Katmai on the Aleutian Islands erupted in 1912. More volcanic explosions of this kind must occur before sufficient data can be obtained to correlate with the predictions of this theory. At the present time it is entirely possible that volcanic dust creates small perturbations in the climate while the general trend is determined by some other factor.

On the other hand the carbon dioxide theory is the only one that predicts a continually rising average temperature for the remainder of this century because of the accumulation of carbon dioxide in the atmosphere as a result of industrial activity. In fact the temperature rise from this cause may be so large in several centuries that it will present a serious problem to future generations. The removal of vast quantities of carbon dioxide from the atmosphere would be an extremely costly operation. If at the end of this century the average temperature has continued to rise and in addition measurement also shows that the atmospheric carbon dioxide amount has also increased, then it will be firmly established that carbon dioxide is a determining factor in causing climatic change.

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Gilbert N. Plass: Climate Science in Perspective

James Rodger Fleming

Gilbert Plass was a scientist on the cutting edge of climate research in 1956. His article in *American Scientist,* on the recently revived carbon dioxide theory of climate change, and the role that the combustion of fossil fuel was playing in it, was aimed at a broadly educated scientific readership; it was one of six related articles he published that year and one of about a dozen he published that decade. In a 1997 interview, Plass told me, “all sorts of things came together” that placed him at the scientific forefront: new detailed laboratory measurements of the absorption bands of water vapor, carbon dioxide and ozone; theoretical developments involving the influence of temperature and pressure on infrared absorption; new information about the carbon cycle and industrial emissions; and access to a new high-speed electronic computer to facilitate complex calculations of radiative transfer that replaced the older, graphical approximations.

Gilbert Norman Plass was born in Toronto, Ontario, Canada, on March 22, 1920. He was a physicist who developed an early computer model of infrared radiative transfer and published a number of articles on carbon dioxide and climate between 1953 and 1959. He received a B.S. from Harvard University in 1941, where he recalled that his courses on geology, chemistry and physics provided an interdisciplinary foundation for his later work. He was particularly impressed by the experimental techniques of John Strong, one of his physics professors. Plass received his Ph.D. from Princeton University in 1947 and worked as an associate physicist at the Metallurgical Laboratory (Manhattan District) of the University of Chicago from 1942 to 1945. He became an instructor of physics at Johns Hopkins University in 1946 and was subsequently promoted to assistant and then associate professor. At Hopkins he conducted research on infrared radiation with funds provided by the Office of Naval Research. During his sabbatical year, at Michigan State University in 1954–55, he gained access to a large computer and realized it offered the perfect way to construct a better model of radiative transfer. In 1955 Plass moved out of academics, serving for a year as a staff scientist with Lockheed Aircraft Corporation. He then joined the advanced research staff of the Aeronutronic division of the Ford Motor Company. Ford provided him with excellent laboratory facilities where he could continue his experimental work on infrared physics. In 1960, he became manager of the research lab at Ford's theoretical physics department and a consulting editor of the journal *Infrared Physics*. In 1963, he accepted a position as the first professor of atmospheric and space science at the Southwest Center for Advanced Studies (now the University of Texas, Arlington) where he remained for five years. In 1968, he arrived at Texas A&M University, where he served as professor of physics and head of the department. He is the author of six books, including *Infrared Physics and Engineering* (1963) and more than 100 articles on radiative transfer and climate change, nuclear fission and neutron physics, electromagnetic and gravitational action at a distance, electron emission, and electrostatic electron lenses. Plass and his spouse were active supporters of the arts, helping to establish and direct arts societies and producing a radio program in Texas. He passed away in Bryan, Texas, on March 1, 2004.

In 1956 Gilbert Plass was heir to a century of work that identified variations in the trace amounts of carbon dioxide in the atmosphere as a possible cause of ice ages and interglacial periods. John Tyndall wrote in 1861 that slight changes in the amount of any of the radiatively active constituents of the atmosphere—water vapor, carbon dioxide, ozone or hydrocarbons—may have produced "*all the mutations of climate which the researches of geologists reveal* … they constitute true causes, the *extent* alone of the operation remaining doubtful." Thirty-five years later Svante Arrhenius published a landmark paper examining the effect of different concentrations of atmospheric CO_2 on the temperature of Earth. His energy budget model, which he calculated by hand, contained estimates of the absorption and emission of terrestrial radiation by water vapor and carbon dioxide, but since infrared research was in its infancy then, Arrhenius had access to only very limited spectroscopic data.

Because of these limitations, the carbon dioxide theory of climate change was in deep eclipse in 1938 when British scientist and engineer Guy Stewart Callendar revived it and placed it on a firm scientific basis. Callendar documented a significant upward trend in temperatures for the first four decades of the 20th century and noted the systematic retreat of glaciers. He compiled estimates of rising concentrations of atmospheric CO_2 since pre-industrial times and linked the rise of CO_2 to the combustion of fossil fuel. Finally, he synthesized information newly available concerning the infrared absorption bands of trace atmospheric constituents and linked increased sky radiation from increased CO_2 concentrations to the rising temperature trend. Today this is called *The Callendar Effect*.

Building on such foundations, Plass was able to take the next steps in research and provide his masterful overview of the carbon dioxide theory and its implications for the future. He established connections between the physics of infrared absorption by gases, the geochemistry of the carbon cycle, feedback loops in the climate system and computer modeling. Using recent measurements of the influence of the 15-micrometer CO_2 absorption band, Plass calculated a 3.6 degrees Celsius surface temperature increase for doubling of atmospheric carbon dioxide and a 3.8 degree decrease if the concentration were halved. Contrary to the assumptions of many scientists at the time, the effect of water vapor absorption did not mask the carbon dioxide effect by any means. He used these results to argue for the applicability of the carbon dioxide theory of climate change for geological epochs and in recent decades.

Stressing the intrinsic role carbon dioxide plays in our atmosphere, Plass discussed the danger of fossil fuel burning and deforestation. The six billion tons of CO_2 being added to the atmosphere each year was sufficient to cause noticeable changes in the Earth's radiation balance and thus the climate. He noted that the observed 1.1 degree rate of climate warming per century was in agreement with the predictions of the carbon dioxide theory.

Waxing prophetic, Plass wrote that the oceans would be able to sequester only a small amount of the anthropogenic carbon, leaving the majority in the atmosphere. Accumulating atmospheric CO_2 content from fossil fuel-based industrial activities would eventually result in a temperature rise of at least 7 degrees. Plass held out little hope for nuclear power—expressing an opinion that would not be widespread for several more decades. Presaging the work of Charles David Keeling, which began two years later, Plass called for new accurate measurements of the increasing CO_2 concentration in the atmosphere, which he rightly estimated should be on the order of 0.3 percent per year. Plass pointed out that humanity was conducting a large-scale experiment on the atmosphere, the results of which would not be available for several generations: "If at the end of this century, the average temperature has continued to rise and in addition measurement shows that the atmospheric carbon dioxide amount has also increased, it will be firmly established that carbon dioxide is a determining factor in causing climatic change."

There have been two interruptions (pauses, if you will) in the rise of global average temperature since 1956, and of course, Earth's climate is influenced by more than just CO_2. Other trace gases and black carbon warm the climate, and aerosols cool it. On a larger scale, the astronomical theory of orbital influences was revived circa 1976, and climate variation attributed to such factors as ENSO, the Pacific Decadal Oscillation, and solar activity (or the lack thereof) are now being widely discussed. Still, more than 50 years later, scientists agree that the uncontrolled experiment pointed out by Plass in 1956 has been verified, and a warmer future caused by the radiative effects of CO_2 is in store. The cutting edge question now is, What to do about it?

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Does Science Progress? Gilbert Plass Redux

Gavin Schmidt

Considering today's concerns about human-driven climate change and the need to cut carbon emissions, it's interesting to look back at a time (not that long ago) when the idea that carbon dioxide (CO_2) affected climate was very much a fringe concern. Gilbert N. Plass's 1956 article (reprinted in this issue of *American Scientist)* was only the start of a quite rocky road to modern respectability for an idea born in the 19th century; even he might be surprised to see how it has become completely mainstream (despite what one might read on the Internet!).

This paper, the insights it contained, and the calculations and forecasts it made actually constitute a great example of how, despite reaching bottom-line conclusions very similar to pronouncements made in the recent Intergovernmental Panel on Climate Change (IPCC) report, the science that underlies those conclusions has improved remarkably. It is also a great example of the role luck plays in determining one's role in scientific prosperity (but more on that below).

Before discussing the detail of what was in that paper, it is worth pointing out what Plass could not have known. He did not know how fast CO_2 was accumulating in the atmosphere—Charles Keeling would start his seminal measurements at Mauna Loa only in 1957. Neither did he know how CO_2 had varied in the past—the first ice core results only emerged in the 1980s. But he was still able, with his understanding of infrared spectroscopy, to write a paper that qualitatively predicted both these results—although with methods that we can now recognise as being incomplete—and correctly concluded that the impact of

CO_2 on climate would be clear by the end of the 20th century. There are other things that we know now that he could not possibly have known—the importance of other greenhouse gases (methane in particular, which wasn't recognised as an important contributor to anthropogenic forcing until 1974, but also chlorofluorocarbons and N_2O, which have also increased dramatically because of human influence) and the role of human-emitted particulates and low-level ozone precursors.

To be sure, there is much that marks the paper out as a product of its era: There is an excessive focus on single-factor explanations of all climate changes and a penchant for what would now be considered naive back-of-the-envelope estimates of the impacts of small changes on very complex systems. And as befits publication in a popular science magazine, there is a lot of big-picture discussion, although perhaps in excess of what would be considered prudent today.

The paper revolves around three main themes: the modern day carbon cycle and the fate of human-produced CO_2, the calculation of the radiative impact of that CO_2 and the resulting temperature rise, and the possibilities for CO_2 playing a role in climate changes in the past. I'll review the first two of these themes and leave the far more speculative discussions about the cause of the ice ages for another time.

Plass knew that atmospheric levels of CO_2 were around 300 parts per million by volume (ppmv) and correctly noted (as had Guy Stewart Callendar almost 20 years earlier) that human use of fossil fuel would lead to an increase in atmospheric levels of CO_2. He was actually a little optimistic, though, in assuming that only 6×10^9 tons of CO_2 per year (equivalent to 1.5 gigatonnes of carbon per year, or GtC/yr) were being emitted. Current estimates suggest that emissions in 1956 were already almost 50 percent higher than that (8.8×10^9 tons CO_2 /yr or 2.2 GtC/yr).

He also understood enough of the terrestrial and oceanic carbon cycle to know that uptake of the anthropogenic carbon would be slow. He had two quite telling insights: First, although the residence time for carbon dioxide in the atmosphere (the total amount of CO_2 divided by the flux in and out of the ocean) is on the order of a few years, the perturbation time is much longer—even up to a few tens of thousands of years—because of the slow uptake in the deep ocean and the buffering effects of the ocean chemistry. Second, he realised that the added carbon in the ocean would cause increasing acidification with consequent impacts on marine life (although he did underestimate how big this effect would be).

Combining the rate of increase of fossil carbon and lack of uptake in the ocean, he estimated that the CO_2 levels might increase 30 percent in a century. Since 1850, CO_2 has actually increased by more than 100 ppmv (36 percent above pre-industrial values), and so this appears to be a reasonable prediction. However, Plass was lucky. In underestimating both the current anthropogenic emissions and the uptake by the ocean, his two errors roughly cancelled.

Plass's real contribution, however, is in his assessment of what that extra CO_2 would do to the climate. His calculations included the fact that you have to consider the whole atmospheric column, and that despite the large amount of water vapor near the surface, there are always large parts of the atmosphere where CO_2 is a very important absorber and emitter. This meant that the impact of changing CO_2 would not be as negligible as had been thought over previous decades. These calculations require good knowledge of how all the various wavelengths are absorbed by each component in the atmosphere (including clouds), and how that changes as a function of temperature and (most importantly) pressure. The data for these absorption spectra have improved enormously in the past 50 years as has the capacity to do all these calculations, so one might anticipate that this is where Plass would have been most overtaken by scientific progress. However, Plass actually did a pretty good job. Converting to more modern units and doing a little publication archaeology, we can see that he estimated the radiative forcing by a doubling of CO_2 in clear sky conditions at 8.3 watts per square meter (W/m^2) and that in cloudy conditions it would be 5.8 W/m^2. The accepted value for the global average today is around 4 W/m^2 with about a 10 percent uncertainty (including both cloudy and clear-sky conditions). Thus while his numbers were a little large, they were within a factor of two of the right answer, and much closer than the near-zero impact that had been previously considered to be the best estimate.

To convert the radiative forcing into a temperature change, Plass relied on a conversion factor of about 0.43°C/(W/m^2) (again, updated to more modern units). This was not independently calculated by him and referred only to the "no-feedback" case where all other atmospheric components (for example, water vapor and clouds) stayed the same. Modern estimates for the no-feedback sensitivity are a little lower (around 0.3°C/(W/m^2)). The basis of his 3.6°C change for a doubling of CO_2 is then seen as a combination of his over estimated forcing and a slightly high no-feedback sensitivity. Modern estimates of this number are around 1.2°C. Plass was aware of the potential for amplifying feedbacks, particularly via water vapor and cloud changes, but the quantification of these effects would have to wait another 10 years for the work of Fritz Möller and subsequently Suki Manabe and colleagues.

Thus even though the headline number in the Plass article is well within the range of the modern IPCC reports (which give a total sensitivity of between 2 to 4.5°C for a doubling of CO_2), it isn't quite fair to give him full credit since his number doesn't include many important factors that he was not able to quantify. Nonetheless, he realized full well the importance of numerical computation for these estimates but was working at the edge of what was then possible.

Similarly, his estimate for the temperature change for the 20th century of 1.1°C was uncannily close to the actual change of roughly 0.7°C. However, as he himself admits, this "could merely be coincidence," and unfortunately I have to confirm that. Two other factors that he was not really aware of complicate this estimate dramatically. The first is the thermal lag of the system due to the heat capacity of the oceans. This delays substantially (by decades to centuries) the full impact of a change in greenhouse gases, as it takes a long time for the ocean surface temperatures to equilibrate with the new radiation balance. Secondly, he probably wasn't aware that other aspects of atmospheric composition—as mentioned above—were being greatly affected by human activity as well.

Nonetheless, a number of conclusions that he drew were almost prophetic. He was correct in assuming (against the conventional wisdom of his time) that moves towards nuclear energy would not make a substantial difference to carbon emissions. He was also correct in thinking that the price of removing the carbon from the air would be prohibitively expensive (as it has turned out, although some progress is being made).

So does science progress? Yes, of course. Gilbert Plass had the right framework for this problem and foresaw most of the issues, but the detailed rendering of the calculations—for the carbon cycle, for the radiative transfer, for the existence of feedbacks, for the temperature response—have all become much more sophisticated and complete. What once were rough estimates have been much more tightly constrained. Speculations about growth rates and past behavior have been confirmed by multiple observations.

Nonetheless, the coincidences of some of his numbers and the ones we know today are just that, coincidences, and so some part of the high regard in which we hold Plass today may simply be due to luck. Indeed, Lewis Kaplan, the author of a subsequent and more accurate calculation, has been all but forgotten since he incorrectly concluded that CO_2 could not play a role in climate change. In 50 years time if someone reviews my work, I would hope to have been as lucky as Gilbert Plass.