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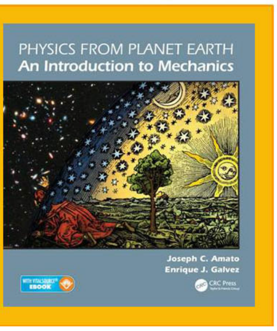

Effect of Carbon Dioxide Variations on Climate*

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Variations in the amount of atmospheric carbon dioxide cause temperature changes sufficiently large to influence the climate. If the atmospheric carbon dioxide doubles, the surface temperature rises 3.6°C; if it is cut in half, the surface temperature falls 3.8°C. Some of the factors that can be explained by the carbon dioxide theory are: during a single glacial epoch, the climate continually oscillates between a glacial and an interglacial stage with a period of tens of thousands of years with no stable state possible, when the carbon dioxide amount is below a certain critical value; the increased precipitation at the beginning of a glacial period; the time lag between the period of mountain building and the onset of glaciation; periods of glaciation occur at the same time in both hemispheres; the general warming of the climate in the last fifty years. The various factors that enter into the carbon dioxide balance and the influence of the oceans on the atmospheric carbon dioxide amount are discussed in detail. In contrast to other theories of climatic change, the carbon dioxide theory predicts a warming trend that will continue for centuries or as long as fossil fuels are burned in significant quantities.

1. INTRODUCTION

THE climate of the earth has changed from periods when most of the earth's surface had a tropical climate to severe glacial epochs many times during its several billion year history. For the past one billion years the earth has been warmer than it is today at least nine-tenths of the time. These warm periods have been interrupted at intervals of roughly 250 000 000 years by severe glacial periods of a few million years duration. In addition, there have been many smaller fluctuations of the climate around these major climatic oscillations. One of these that is of particular interest to our present generation is the general rise in temperature that has occurred in the last sixty years.

Many different theories have been proposed in order to explain these climatic changes. At the present time the most widely held theories 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 each of these factors may have had some influence on the climate at a particular time and place in the earth's history, no one of these theories alone is able to explain a majority of the known facts about climatic change.

Fifty years ago the carbon dioxide theory was perhaps the most widely held theory of climatic change, but in recent years it has had relatively few adherents. However, recent research suggests that the usual reasons for rejecting this theory are not valid. Therefore it seems appropriate to re-examine the question of the influence of variations in the amount of carbon dioxide on the climate in order to see whether it can satisfactorily explain most of the known facts about world-wide climatic change.

Physicists are perhaps somewhat partial to the carbon dioxide theory since all of the relevant experimental and theoretical work that is needed in order to determine the magnitude of the effect is in their field. As long ago as 1827, Fourier[1] compared the influence of the atmosphere to the heating of a closed space beneath a pane of glass. However, Tyndall[2] in 1861 gave the first clear statement of the carbon dioxide theory of climatic change. He wrote that, "if, as the above experiments indicated, the chief influence be exercised by the aqueous vapour, every variation of this constituent must produce a change of climate. Similar remarks would apply to the carbonic acid diffused through the air .... It is not, therefore, necessary to assume alterations

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* This work was supported by the Office of Naval Research.

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[1] M. Fourier, Mem. de l'Academie Royale des Sciences de l'Institut de France 7, 569 (1827).

[2] J. Tyndall, Phil. Mag. 22, 169, 273 (1861).

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in the density and height of the atmosphere to account for different amounts of heat being preserved to the earth at different times; a slight change in its variable constituents would suffice for this. Such changes in fact may have produced all the mutations of climate which the researches of geologists reveal. However this may be, the facts above cited remain: they constitute true causes, the *extent* alone of the operation remaining doubtful." A century of scientific work has been necessary in order to calculate with any certainty the extent of the influence of carbon dioxide.

During the nineteenth century, Arrhenius[3] made the most extensive calculations of the magnitude of the carbon dioxide effect. The geological implications of the carbon dioxide theory were considered at length in a series of articles by Chamberlin.[4]

The carbon dioxide theory is based on the known properties of this gas to absorb radiation in the infrared portion of the spectrum. None of the three most abundant gases (oxygen, nitrogen, argon) in the atmosphere absorb appreciably in the range of frequencies in the infrared that are emitted by the earth's surface and atmosphere. If our atmosphere consisted entirely of these three gases, our climate would be very different. The average temperature would be very much colder, since the heat from the surface of the earth could escape virtually unobstructed to space. Fortunately for us there are three other gases (carbon dioxide, water vapor, ozone) that occur in the atmosphere in relatively minute quantities and that do absorb radiation over at least a portion of the appropriate frequency range in the infrared. Carbon dioxide is fairly uniformly mixed throughout the atmosphere; its concentration is about 0.03% by volume. The amount of water vapor and ozone varies with time and place, but these gases never occupy more than a small part of the atmosphere.

The amount of these three relatively rare gases determines our climate to a large extent. Their action has often been compared to the heating of an inclosed space with glass windows. Everyone is familiar with the almost unbearable heat inside an automobile that has been standing in the summer sun with closed windows. The rays of the sun come in through the glass which is transparent in the visible. However, the outgoing radiation from the interior of the automobile is in the infrared at frequencies where glass is largely opaque. The heat energy is thus effectively trapped inside this inclosed space and the temperature rises appreciably.

In the same manner the atmosphere acts to control the temperature at the surface of the earth. The atmosphere is largely transparent to the visible rays from the sun and it allows this energy to get down to the surface of the earth. But this energy must also be held near the surface of the earth and not immediately reradiated to space, if we are to have a warm climate. The outgoing infrared radiation is partially absorbed by the carbon dioxide, water vapor and ozone. Each of these gases absorbs in a different region of the spectrum. The carbon dioxide theory states that there is a greater absorption of the outgoing radiation if the amount of carbon dioxide in the atmosphere is increased; thus the heat is kept near the surface and the surface temperature rises.

Because of the great complexity of the infrared bands of carbon dioxide with their many hundreds of overlapping spectral lines, the early calculations of the carbon dioxide effect necessarily used many approximations and the final result was very uncertain. Recently it has been possible to calculate the carbon dioxide effect with considerably improved accuracy because of recent accurate absorption measurements in the infrared[5] and the availability of high-speed electronic computors. The results of the latest calculations[6] show that, if the carbon dioxide content of the atmosphere should double, the surface temperature would rise 3.6°C and if the amount should be cut in half, the surface temperature would fall 3.8°C. This result assumes that no other factor that influences the radiation balance, such as mean cloud amount, changes as the carbon dioxide content varies. This question is discussed in more detail in Sec. 4.

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[3] S. Arrhenius, Phil. Mag. **41**, 237 (1896).

[4] T. C. Chamberlin, J. Geology **5**, 653 (1897); **6**, 609 (1898); **7**, 545, 667, 751 (1899).

[5] W. H. Cloud, "The 15 micron band of CO_2 broadened by nitrogen and helium," ONR Progress Report, Johns Hopkins University, Baltimore (1952).

[6] G. N. Plass, Am. J. Phys. **24**, 303 (1956).

The usual objection to the carbon dioxide theory, found in almost every textbook, is that water vapor absorbs in the same spectral region as the carbon dioxide. According to this argument, water vapor absorption is sufficiently large so that it, rather than the carbon dioxide, controls the radiation in this spectral interval. However, this conclusion is based on early, very approximate treatments of this problem; all of the details concerning the line structure of the spectrum and of the distribution of water vapor with height are ignored. Even though there is a region where the spectra of these two gases overlap, the water vapor has a relatively small influence on the carbon dioxide since the individual spectral lines of these gases occur at random with respect to each other; detailed calculation shows that they only slightly interfere.

Furthermore, the percentage of water vapor in the atmosphere falls off very rapidly with height (often approximately as the fourth power of the pressure), whereas the carbon dioxide is nearly uniformly distributed throughout the atmosphere at all heights (up to at least 60 km). Even if it is assumed that the water vapor would control the radiation in this spectral interval at the surface of the earth, calculations show that its effect would be negligible just a short distance above the earth's surface. Although it is not yet possible to calculate the influence of water vapor as accurately as for carbon dioxide alone, careful estimates show that water vapor should not reduce the temperature changes given above for carbon dioxide by more than 20% at most. However, this correction is at least partially compensated by the carbon dioxide spectral lines that are outside the 12- to 18-micron region included in the foregoing calculation. Thus the actual temperature change due to carbon dioxide variations is probably very close to the original figures given previously.

The argument has sometimes been advanced that the carbon dioxide cannot cause a temperature change at the surface of the earth because the carbon dioxide band is always completely opaque at any reasonable concentration. Although it is true that the band is opaque near its center, the aforementioned argument completely neglects the many hundreds of spectral lines that are more than one micron from the band center. It is these latter spectral lines that are entirely responsible for the influence of the carbon dioxide concentration on the radiation flux and the equilibrium temperature.

Thus it seems that there is no fundamental objection to the carbon dioxide theory. Further the temperature changes mentioned are more than sufficient to produce significant climatic variations. A very small change in the average temperature has a large influence on the climate. Estimates of various authorities for the average temperature decrease that would bring back a period of glaciation vary from 1.5 to 8°C. A rise in the average temperature of perhaps only 4°C would bring tropical climates to a large fraction of the earth's surface.

Before discussing the explanation of climatic change that is offered by the carbon dioxide theory, we must first investigate the various factors that influence the carbon dioxide balance and also the exchange of carbon dioxide between the oceans and the atmosphere.

2. THE CARBON DIOXIDE BALANCE

The carbon dioxide balance has been discussed by many authors in recent years. Rubey[7] has made one of the most extensive studies of the carbon dioxide equilibrium. Numerous references to the literature are given in the fascinating book about climatic changes edited by Shapley.[8]

Estimates of the magnitude of some of the principal factors that influence the atmospheric carbon dioxide concentration at the present time are given in Table I. Most of these factors are known only to an order of magnitude; naturally, the estimates of different authors vary widely. An attempt has been made to average some of the more careful estimates for each factor.

The largest loss of carbon dioxide from the atmosphere is due to the process of photosynthesis. Estimates made by reliable scientists of the amount used vary from 7 to 200×10^9 tons per year. A value of 60×10^9 tons per year has been adopted as a reasonable value for the purposes of this discussion. Regardless of the exact value, precisely the same amount of carbon

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[7] W. W. Rubey, Geol. Soc. Am. Bull. **62**, 1111 (1951).

[8] *Climatic Change: Evidence, Causes, and Effects*, edited by H. Shapley (Harvard University Press, Cambridge, 1953).

dioxide is returned to the atmosphere each year by all of the processes of respiration and decay of plants and animals, provided 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 relatively small (0.01×10^9 tons per year) and can be neglected in a discussion of the balance of factors from the organic world.

If this steady-state balance between the absorption and emission of carbon dioxide is disturbed, for example, by a sudden increase in the amount of carbon dioxide in the atmosphere, it is known that the amount used in photosynthesis would increase. However, in a very few years, the amount released by the processes of respiration and decay would also increase. Since an average carbon atom that has been used in photosynthesis returns to the atmosphere from the biosphere in about ten years and virtually all the carbon atoms return in 250 years, it follows that the absorption and emission of carbon dioxide would again be in balance in a very few years. Except for a relatively small initial loss from the atmosphere to the biosphere while the new equilibrium is being established, the organic world would not absorb any of the additional carbon dioxide that was postulated to have been released into the atmosphere.

The factors from the inorganic world that contribute to the carbon dioxide balance are also approximately equal today. The most important of these factors are the release of carbon dioxide from the interior of the earth by hot springs, volcanoes, and other sources (0.1×10^9 tons per year added to the atmosphere) and the formation of carbonates in the weathering of igneous rocks (0.1×10^9 tons per year lost from the atmosphere).

TABLE I. Major factors in the carbon dioxide balance at the present time.

Photosynthesis	$-60\ \times10^9$ tons/year	organic world
Decay, respiration	$+60\ \times10^9$	
Formation of new coal beds and other organic deposits	$-\ 0.01\times10^9$	
Weathering of igneous rocks	$-\ 0.1\ \times10^9$	inorganic world
Released from interior of earth by hot springs, volcanoes, etc.	$+\ 0.1\ \times10^9$	
Combustion of fossil fuels; clearance of forests; cultivation of land	$+\ 6.0\ \times10^9$	man's activities

Although these factors are approximately in balance today, it is obvious their contribution to the carbon dioxide balance has changed by large amounts during the geological history of the earth. The carbon dioxide lost by the formation of new coal beds and other organic deposits and by the weathering of igneous rocks and deposition of carbonates has varied widely, as has the carbon dioxide added to the atmosphere by such factors as the evolution of carbon dioxide from hot springs, volcanic vents, gas wells and other sources. Since the variations in these factors occur independently of each other, the net gain or loss of carbon dioxide by the atmosphere from these factors must have changed frequently on a geological time scale. Although it is not always easy to deduce the net result of these many independent variations for a given epoch, the mere knowledge that these factors have changed many times in the past has important implications for studies of the climate.

In recent years industrial and other activities of man have been adding considerably more carbon dioxide to the atmosphere than any of the above factors from the inorganic world (Table I). The combustion of fossil fuels is adding 6×10^9 tons per year of carbon dioxide to the atmosphere at the present time. In addition such activities as the clearance of forests, the drainage and cultivation of lands, and industrial processes such as lime burning and fermentation release additional amounts of carbon dioxide that are not included in the foregoing estimate. This is a large enough contribution to upset the carbon dioxide balance and to increase the amount in the atmosphere appreciably. Some of this additional carbon dioxide is used in photosynthesis, but as already discussed, very little of the extra carbon dioxide is permanently lost to the atmosphere since there is a corresponding increase in the rates of decay and respiration. Another part of this additional carbon dioxide is absorbed by the oceans; this factor is discussed in detail in the following sections. However, it seems probable that these losses are small at the present time. If this is true, then a major portion of the extra carbon dioxide from man's activities will remain in the atmosphere and the carbon dioxide concentration will increase for at least several centuries to come. If this extra carbon dioxide remains in the atmosphere, the concentration is increasing from this source at the rate of 30% a century.

3. EXCHANGE OF CARBON DIOXIDE BETWEEN THE ATMOSPHERE AND OCEANS

Before an attempt is made to explain climatic variations by the carbon dioxide theory, it is important to consider the exchange of carbon dioxide between the atmosphere and the oceans. 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 stages of ionization. If the carbon dioxide pressure in the atmosphere falls below the value for equilibrium with the oceans, then additional carbon dioxide is released to the atmosphere by the oceans. Similarly if the atmospheric carbon dioxide amount is too large for equilibrium, the oceans absorb the excess.

The chemical equations that describe the equilibrium between the relevant ions in sea water can be written down in principle without difficulty. The amount of dissolved carbon dioxide as well as the concentrations of the following ions enters into these equations: HCO_3^-, $CO_3^=$, $H_2BO_3^-$, H^+, OH^-. Since sea water is a strong electrolyte, it is necessary to measure the apparent dissociation constants that enter into these equations. Because of the practical importance of this problem, it has been considered by a number of investigators.[7,9–11]

For the generally accepted values for the apparent dissociation constants, it is found that the oceans are nearly in equilibrium today with an atmospheric carbon dioxide pressure of 3.0×10^{-4} atmos. It is assumed that the average ocean temperature is 8°C, the *p*H (measure of hydrogen ion concentration) is 8.17 and the cholorinity (measure of amount of dissolved salts) is 19.5 ‰. Average values for the concentration of the carbonate ions in the present oceans are as follows: $[CO_2]=1.41\times10^{-5}$ moles/l; $[HCO_3^-]=1.89\times10^{-3}$ moles/l; and $[CO_3^=]=0.204\times10^{-3}$ moles/l.

From the known volume of the oceans and the atmosphere it is found that there are 130×10^{12} tons of carbon dioxide (in the form of carbonates and dissolved gas) in the oceans today and 2.33×10^{12} tons of carbon dioxide in the atmosphere or a total of 132×10^{12} tons of carbon dioxide in the atmosphere-ocean system. Thus the oceans contain over fifty times as much carbon dioxide as the atmosphere. In Fig. 1 the present value for the atmospheric carbon dioxide pressure and the total carbon dioxide amount is marked "*P*."

In order to relate these results to the carbon dioxide theory of climatic change, the equilibrium carbon dioxide pressure in the atmosphere must be known as a function of the total carbon dioxide amount in the atmosphere-ocean system. This has been calculated from the chemical equations described above by Plass[12] with the additional assumptions that the average temperatures of the oceans and land surface of the earth are the same and change with the carbon dioxide concentration by the factor calculated from the infrared equilibrium.[6] Spe-

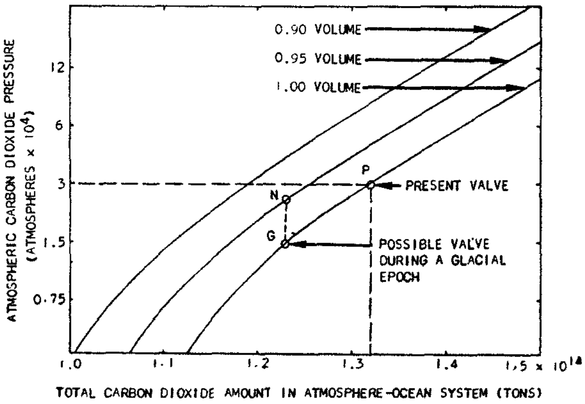

FIG. 1. Equilibrium amounts of carbon dioxide for the atmosphere-ocean system. The ordinate is the logarithm of the carbon dioxide pressure in the atmosphere; the abscissa is the corresponding total carbon dioxide amount present in both the oceans and atmosphere at equilibrium. Each set of curves is given when the oceans have a volume equal to 0.90, 0.95, and 1.00 times their present volume. The carbon dioxide pressure today is marked by the point *P*. The points *G* and *N* represent possible conditions when glaciers are forming and melting, respectively. The dashed line between *G* and *N* represents the typical oscillations in the climate during a glacial epoch.

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[9] Sverdrup, Johnson, and Fleming, *The Oceans: Their Physics, Chemistry, and General Biology* (Prentice-Hall, Inc., New York, 1942).

[10] H. W. Harvey, *Recent Advances in the Chemistry and Biology of Sea Water* (Cambridge University Press, New York, 1945).

[11] A. N. Dingle, Tellus **6**, 342 (1954).

[12] G. N. Plass, Tellus (to be published).

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cifically it was assumed that the average temperature of the oceans was 15.0°C when the carbon dioxide pressure was 12×10^{-4} atmos; 11.6°C when it was 6×10^{-4} atmos; 8.0°C when it was 3×10^{-4} atmos; 4.2°C when it was 1.5×10^{-4} atmos; 0.5°C when it was 0.75×10^{-4} atmos. Although the apparent dissociation constants vary with the temperature, the curves shown in Fig. 1 are insensitive to the particular assumption that is made about their temperature variation. The equilibrium values of the carbon dioxide pressure for various total carbon dioxide amounts in the atmosphere-ocean system are shown in Fig. 1 as the curve marked "1.00 Volume."

Curves are also given in Fig. 1 when the oceans have 0.90 and 0.95 times their present volume, since the large amount of water frozen in the glaciers decreases the ocean volume during a period of glaciation. Estimates show that water having a volume from 5 to 10% of that of the oceans was frozen in the glaciers at the period of the last advance of the ice sheets.[8,13] This number may have been even larger during earlier great epochs of glaciation. Further, the volume of the oceans has probably changed during the recorded geological history of the earth by the addition of juvenile water from the interior of the earth.

Rubey[7] has emphasized that the oceans must reach equilibrium with calcium carbonate after a sufficient period of time following a change in the total amount of carbon dioxide in the atmosphere-ocean system. If there is an excess amount of calcium carbonate, it precipitates; if there is too little calcium carbonate, it dissolves and at the same time accumulates from the rivers that flow into the oceans until the solubility product is reached. The equilibrium carbon dioxide pressure can be obtained when there is calcium carbonate equilibrium by solving the previously mentioned chemical equilibrium equations together with the equation representing the dissociation of calcium carbonate. When this is done, curves similar to those shown in Fig. 1 are obtained, but with a greater slope. Further details are given by Plass.[12] The oceans also appear to be approximately in equilibrium with calcium carbonate today, if the best values of the dissociation constant are used in the equations. The time necessary to reach calcium carbonate equilibrium is not known, but is probably many tens of thousands of years.

It would also be very interesting to know how long it takes the atmosphere-ocean system to return to equilibrium after a change in the atmospheric carbon dioxide pressure. Only the surface waters of the oceans can absorb directly from the atmosphere. Since there is very little circulation between the surface waters and the ocean depths, the time for this sytem to come to equilibrium is probably at least as long as the turnover time for the oceans. Recent radiocarbon determinations by Kulp[14] have shown that the deep ocean waters at the latitude of Newfoundland were at the surface about 1700 years ago. This suggests that it may take tens of thousands of years for the waters of the deep oceans to make one complete circuit from the surface to the bottom and back. If this is the case, it may easily take a similar period of time for the carbon dioxide equilibrium to be re-established following some disturbing factor.

4. CLIMATIC CHANGE

Since the change in surface temperature for a given variation in the atmospheric carbon dioxide amount can be calculated fairly accurately, it remains for the carbon dioxide theory to predict variations in the carbon dioxide amount in the past geological epochs and to correlate these variations with the climate. Although there is no way at present of deducing the atmospheric carbon dioxide content of all past epochs, it is possible to compare the carbon dioxide variation that would be expected in different situations with the corresponding climatic change found in the geological record. It seems significant that the carbon dioxide theory can explain a large number of these climatic variations in a simple manner. Let us examine some of these explanations.

No other theory is able to explain in a simple and straightforward manner the continual oscillations in climate with alternate periods of advance and retreat of glaciers during a million-year epoch of glaciation. Four distinct periods

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[13] R. F. Flint, *Glacial Geology and the Pleistocene Epoch* (John Wiley and Sons, Inc., New York, 1947).

[14] J. L. Kulp, Scientific Monthly **75**, 259 (1952).

of glaciation in the last glacial epoch have been known to geologists for many years. Recent analysis of the sediments of the deep ocean floor by Wiseman[15] show ten distinct temperature minima within the last 620 000 years. A characteristic property of a glacial period is a constantly changing climate. It is interesting that this is just the result that is predicted by the carbon dioxide theory.

In order to understand this phenomenon more clearly, let us assume some particular numbers that may represent conditions at the onset of a typical glacial period; none of the conclusions reached depends on the particular values chosen. First we assume that if the average temperature of the earth should fall 3.8°C (various authorities give values from 2°C to 8°C) that great ice sheets would again begin to cover sizeable portions of the continents. Further let us assume that the average period of circulation for the deep waters of the ocean is of the order of ten thousand years. It must take several of these periods for the atmosphere-ocean system to come to equilibrium after a change in the carbon dioxide amount; the time to return to equilibrium might perhaps be estimated as of the order of 50 000 years, although this time may actually be ten times longer or shorter than this.

Let us suppose that at the beginning of a glacial period for some reason the total amount of carbon dioxide in the atmosphere-ocean system is reduced 7% from its present value of 132×10^{12} tons to 123×10^{12} tons and *remains fixed* at the latter value throughout the glacial epoch of some million years duration. After the atmosphere and ocean have returned to equilibrium (point G in Fig. 1), the carbon dioxide pressure in the atmosphere is 1.5×10^{-4} atmos, just one-half of its former value. The average temperature at the surface of the earth is then 3.8°C less than its former value. This is a sufficient reduction in the temperature to bring on glaciation according to our hypothesis. Let us assume that after some thousands of years the large ice sheets that have formed reduce the volume of the oceans by 5%. Since the ice sheet can permanently hold only a very small amount of carbonates compared to the same volume of ocean water, the remaining water in the oceans releases carbon dioxide to the atmosphere in order to return to equilibrium.

After some tens of thousands of years, the atmosphere-ocean system again reaches equilibrium at the point N in the figure corresponding to an ocean volume of 95% of its present value and with an atmospheric carbon dioxide pressure of 2.5×10^{-5} atmos. With this amount of carbon dioxide in the atmosphere the surface temperature must now rise to practically its present value, but it is then too warm to maintain the ice sheets. They melt and the oceans return to their original volume. Now once again the atmosphere and oceans are no longer in equilibrium, since the oceans do not contain enough carbonates for their increased volume. The ocean starts absorbing carbon dioxide from the atmosphere and after another period of tens of thousands of years, the system is in equilibrium again at the point G of the figure. But now the lower carbon dioxide pressure reduces the surface temperature 3.8°C and another ice sheet starts to form. The cycle continues indefinitely as long as the total carbon dioxide amount remains fixed at the value 1.23×10^{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.

There is no point in this cycle of events where the climate is stable; it must continually oscillate from a glacial to an interglacial period. In order to picture the changes in this cycle more clearly, some specific numbers have been assumed. However, one can easily verify that these numbers can be changed by any reasonable amount without altering the conclusions derived in the foregoing. If the total carbon dioxide amount including that in the oceans should be reduced greatly below its present value, perhaps by 30% or more, then a permanent period of glaciation could begin. But as long as the total carbon dioxide amount is reduced only a moderate amount below its present value, then the oscillations from a glacial to an interglacial climate and back always occur. It should be mentioned that, if it is assumed in addition that the oceans have sufficient time in the various stages of the cycle to come to equilibrium with calcium carbonate, none of the conclusions

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[15] J. D. H. Wiseman, Proc. Roy. Soc. (London) **A222**, 296 (1954).

reached above is essentially altered even though the form of the curves in Fig. 1 is then slightly different.

It has been emphasized by many authors that not only lower temperatures, but also increased precipitation are necessary for the accumulation of extensive ice sheets. It has been very difficult for most theories of climatic change to account for this increased precipitation. For example, according to the variable sun theory a decrease in the energy from the sun would lower the temperature, but it would also provide less energy to drive the general circulation of the atmosphere; presumably this would reduce the precipitation as well. In order to account for the increased precipitation, an ingenious but unconvincing modification of the variable sun theory claims that glacial periods result from an increase in the sun's radiations. The slightly increased temperature is supposed to be more than offset by the increased precipitation. The carbon dioxide theory offers a simple, direct explanation of the increased precipitation.

Although the physical processes that cause precipitation from a cloud are not completely understood, the radiation loss from the upper surface of a cloud is known to be one of the relevant parameters. If the upper surface of the cloud can lose more heat by radiation, it becomes colder, thus increasing the temperature difference between the upper and lower surface of the cloud. This provides more energy to increase the convection inside the cloud, which in turn hastens the onset of precipitation.

The temperature difference between the upper and lower cloud surfaces would be expected to be greater at night than during the day and more precipitation is observed at night.[16] It appears that the radiation loss from the upper surface of the cloud is an important factor in the development of nocturnal thunderstorms; in other situations the relative importance of this factor is not known.

During the period when glaciers are forming there is a smaller than normal amount of carbon dioxide in the atmosphere. More radiation from the upper surface of a cloud is able to escape to space, thus cooling the upper surface more effectively. Calculations by Plass[17] show that the average temperature is lowered 2.2°C and 1.3°C for the upper surface of a cloud at 4 km and 9 km, respectively, if the amount of carbon dioxide in the atmosphere is halved. Further the temperature at the lower surface of the cloud increases somewhat as the carbon dioxide amount decreases. The increased convection within the cloud due to the larger temperature difference at its upper and lower surfaces should be more than sufficient to increase the average precipitation significantly. In addition the increased cloud cover as the carbon dioxide amount decreases prevents the sun's radiations from reaching the earth and further reduces the surface temperature below the amount calculated from the infrared equilibrium alone. It is not possible to make a quantitative estimate of this effect at the present time. Both the decreased average temperature and the increased precipitation caused by the reduction in the atmospheric carbon dioxide content effectively promote the growth of ice sheets. Thus according to the carbon dioxide theory, cold and wet climates should occur together.

There is considerable geological evidence that extensive outbursts of mountain building preceded each of the last two major glacial epochs by at least several million years. Again the carbon dioxide theory seems to be the only theory that provides an explanation for the time lag between these two events. Tremendous quantities of igneous rock are exposed to weathering by mountain building. By far the most active zone for the disintegration of rock is the zone between the surface and the level of the permanent underground water. In mountainous country this level is farther below the surface than in flat country and there is a considerably larger volume in which the active weathering of the rocks takes place. In the weathering of igneous rocks carbonates are formed, thus removing carbon dioxide from the atmosphere.

After a period of mountain building, more carbon dioxide is being taken from the atmosphere in the weathering of rock than before. This could easily change the carbon dioxide

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[16] E. W. Hewson, Quart. J. Roy. Meteorol. Soc. **63**, 323 (1937).

[17] G. N. Plass, Quart. J. Roy. Meteorol. Soc. (to be published).

balance sufficiently so that after a period of the order of a million years, the atmospheric carbon dioxide would be reduced sufficiently to start a period of glaciation.

However, the time lag before the appearance of the glaciers may be even further increased by carbon dioxide that is released into the atmosphere from the interior of the earth through volcanic vents and hot springs. Such activity should increase at the time of mountain building. An additional period would be needed to use up this extra carbon dioxide in weathering. If too much carbon dioxide were released from the interior of the earth, the amount in the atmosphere might always be too large to permit a glacial period. In fact, some major periods of mountain building have not been followed by extensive glaciation. A possible explanation would be that more carbon dioxide had been added to the atmosphere from the interior of the earth than could later be removed by rock weathering. In any case, when a glacial epoch does follow a period of mountain building, the carbon dioxide theory clearly predicts an appreciable time delay between the two events.

If the carbon dioxide amount is suddenly increased in one hemisphere, it will be distributed uniformly over both hemispheres in a relatively short time, probably less than a few decades. Thus any large scale climatic variations due to carbon dioxide must occur in both hemispheres at the same period. Radiocarbon dating and other methods indicate that the major changes in the last ice sheets were contemporaneous in both hemispheres. Also, in the last half century the glaciers in both hemispheres have been receding. An exception to the rule of simultaneous climatic variations in both hemispheres could occur if the topography of the two hemispheres were very different. There might be large mountain ranges in one hemisphere that would provide a region for the accumulation of ice and snow sufficient to start a large glacier. If there were no such mountainous region in the other hemisphere, it is possible that the temperatures might not be low enough to start the formation of large ice sheets there.

Another factor in the carbon dioxide balance that has varied widely during the geological history of the earth is the amount of organic material being trapped in new coal and oil deposits and other sediments. This is a relatively small amount at the present time, but must have been much larger during the Carboniferous period. Most of our coal deposits were formed then; the land was relatively flat and a large number of marshes provided the proper conditions for the formation of these deposits. After a long period of time this accumulation reduced appreciably the amount of carbon dioxide available to the atmosphere-ocean system. It is perhaps significant that the glaciation at the end of the Carboniferous may have been the most severe in the earth's history.

Some of the possible explanations for past climatic change have been discussed above. The carbon dioxide theory may also provide an explanation of the recent warming of the climate over the past half-century. We have already mentioned that 6×10^9 tons of carbon dioxide are being added to the atmosphere each year by the burning of fossil fuels. Other activities of man such as the clearance of forests and the drainage and cultivation of land add additional amounts of carbon dioxide to the atmosphere each year. The total amount added each year from these sources is several orders of magnitude larger than any factor that contributes to the carbon dioxide balance from the inorganic world at the present time (see Table I). Therefore, this additional factor has greatly disturbed the carbon dioxide balance. If all this additional carbon dioxide remains in the atmosphere, there will be 30% more carbon dioxide in the atmosphere at the end of the twentieth century than at the beginning. If no other factors change, man's activities are increasing the average temperature by 1.1°C per century. This argument was first presented by Callendar.[18]

There appear to be only two ways in which this excess carbon dioxide can be removed from the atmosphere in large quantities. As the carbon dioxide amount increases, more is used in photosynthesis. However, as previously discussed, in a relatively short time the increased rates of respiration and decay again bring the factors from the organic world into balance. Except for an initial loss while the equilibrium is being

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[18] G. S. Callendar, Quart. J. Roy. Meteorol. Soc. **64**, 223 (1938); Weather **4**, 310 (1949).

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reestablished, it does not seem that this source can use up any appreciable fraction of the additional carbon dioxide.

The extra carbon dioxide can also be absorbed by the oceans, since the atmosphere-ocean system will no longer be in equilibrium with the higher carbon dioxide amounts in the atmosphere. However, because of the slow circulation of the ocean waters, it would probably take at least 10 000 years for this system to come to equilibrium after a sudden change in the carbon dioxide amount. Nevertheless the surface layers of the ocean start absorbing some of the extra carbon dioxide from the atmosphere at once. It is not known how rapidly this absorption takes place, but it is probably true that the surface layers can absorb only a small fraction of the extra carbon dioxide in a period of several hundred years. Thus it appears that most of the additional carbon dioxide that is released into the atmosphere will accumulate there for at least several centuries. Even if the oceans absorb carbon dioxide much more rapidly than has been assumed here, the accumulation of carbon dioxide in the atmosphere will become an increasingly important problem through the centuries.

The known reserves of coal and oil amount to about 13×10^{12} tons. After making allowance for the growth of industrial activity it is expected that this amount of fuel will be used up in less than one thousand years. If this occurs, nearly 40×10^{12} tons of carbon dioxide will have been added to the atmosphere. This is seventeen times the present amount of carbon dioxide in the atmosphere. Even if it is assumed that the the atmosphere-ocean system will be near equilibrium at the end of this period, the total carbon dioxide amount will increase from 132×10^{12} tons to 172×10^{12} tons. From an extension of Fig. 1 the equilibrium value of the carbon dioxide pressure is found to be 30×10^{-4} atmos corresponding to a temperature rise of 12.2°C. Even if there were sufficient time for calcium carbonate equilibrium to set in, calculation shows that the carbon dioxide pressure is 11×10^{-4} atmos (nearly four times the present value) and the corresponding temperature rise is 7.0°C. Since complete equilibrium between the atmosphere and oceans can not be maintained when the atmospheric carbon dioxide amount is constantly increasing, the actual temperature rise will be considerably greater than 7°C.

Thus the accumulation of carbon dioxide in the atmosphere is seen to be a very serious problem over periods of the order of several centuries. It is interesting that two of the most important methods available at the present time for generating large amounts of power have serious disadvantages when used over long time intervals. The burning of fossil fuels increases the temperature of the earth from the carbon dioxide effect; the use of nuclear reactors increases the radioactivity of the earth. It is difficult to say which of these effects would be the less objectionable after several centuries of operation.

There are many questions which remain to be answered about the carbon dioxide theory, principally because we do not know the exact carbon dioxide content of the atmosphere during a given period of the earth's history. Unfortunately we can not even say with certainty whether or not the carbon dioxide content of the air has increased since the year 1900. Many accurate measurements were made at the turn of the century, but there have been relatively few recently. The available data suggests that the carbon dioxide content of the atmosphere has increased 10% in this period, but more measurements are needed to establish this definitely. In view of the importance of this factor for the climate these measurements should be made regularly at several different locations for some years.

The carbon dioxide theory has plausible explanations of the beginning of a glacial period and of the climatic oscillations throughout the glacial period. What factor brings a glacial period to a close? The increase in the total carbon dioxide amount in the atmosphere may be caused by a reduced amount of rock weathering. The increasing flatness of the land as the mountains erode and the fraction of the land surface that has been covered by glaciers during the preceding epoch reduce the rock weathering. According to the carbon dioxide theory the reason for recurrent periods of glaciation at intervals of approximately 250 000 000 years is that mountain building occurred at similar periods.

Some interesting evidence about the carbon dioxide content of the atmosphere in the past can be deduced from the fact 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 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 the carbon dioxide concentration has been at a higher level during the majority of the ensuing time. This higher carbon dioxide concentration would have caused higher temperatures than today during most of the earth's history. In fact, the geological evidence shows that the earth has had a warm climate for at least nine-tenths of the time since the Cambrian period.

Some further evidence for past carbon dioxide variations is that higher marine animals, herring, for example, can not tolerate *p*H changes of more than ±0.5 in the sea water and that lower marine animals, sea urchins, diatoms, and algae, although less sensitive, can not tolerate *p*H changes of more than ±1.0. This suggests that, during the geological periods in which these animals have lived, the *p*H of the sea has either stayed constant within these limits or at most has changed very slowly so that the animals have had a chance to adapt to their new environment. However, the atmospheric carbon dioxide pressure can vary by a factor of fifty without changing the *p*H of sea water by more than one-half unit. Thus relatively rapid changes in carbon dioxide amount of this magnitude may have occurred in the earth's atmosphere without influencing either land or sea animals; larger changes may have taken place over very long periods of time so that the animals could adapt to these variations.

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 the radiocarbon dates for events *before* the recession of the glaciers are in question. A constant carbon dioxide amount in the atmosphere has been assumed in all of the calculations to determine radiocarbon dates. Clearly some direct evidence is needed for the actual carbon dioxide amount in past epochs. It is possible that this may be calculated in the future from experimental determinations of the past temperature of the oceans and the rate of carbonate deposition.

Two other atmospheric gases, water vapor and ozone, absorb appreciably in the infrared in the appropriate spectral range to influence the temperature near the surface. Any change in their average amounts and distribution would also change the climate. Strong winds sometimes carry the ozone down to lower altitudes where the ozone concentration is usually small. When this happens, recent calculations[19] have shown that the surface temperature can rise appreciably. Accurate calculations for water vapor have not been made as yet, but there is no doubt that a similar effect exists for this gas. It is much more difficult to estimate how the relative amounts of these two gases have varied in the past than it is for carbon dioxide. Few suggestions have been made to date that relate climatic changes to variations in the amount and distribution of these two gases.

How can we decide what is really the most important factor of the many that have been proposed to explain world-wide climatic changes? The temperature trend during the remainder of this century should provide a definitive test of the relative importance of such factors as carbon dioxide, variations in the solar energy, and volcanic dust in determining the climate at the present time. The predictions based on these theories are entirely different. Each theory has to meet a continually more rigorous test as more and more facts are found about past variations in climate and the relevant parameters of the various theories. The volcanic dust theory correlates a lower average temperature with a major volcanic explosion which sends large amounts of dust into the atmosphere. There has been no such explosion since 1912 when Katmai erupted in the Aleutian Islands. Further at-

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[19] G. N. Plass, Quart. J. Roy. Meteorol. Soc. **82**, 30 (1956).

tempts at verification of this theory must await new volcanic action.

On the other hand the variable sun theory predicts that the average temperature will decrease for some decades. The maximum of the eighty-year period in the sunspot cycle probably occurred in 1947. The energy that the earth receives from the sun including the ultraviolet should decrease for a number of years when averaged over the shorter cycles; thus the prediction is that the average temperature will decrease for this period. A continued temperature rise could not be explained by the solar theory unless measurements at the same time should show an appreciable increase in the solar constant.

The carbon dioxide theory alone predicts that the temperature must continue to rise for at least several centuries over the entire world. The accumulation of carbon dioxide in the atmosphere from continually expanding industrial activity may become a real problem in several generations. If at the end of this century, measurements show that the carbon dioxide content of the atmosphere has risen appreciably and at the same time the temperature has continued to rise throughout the world, it will be firmly established that carbon dioxide is an important factor in causing climatic change.

5. CONCLUSION

It is now possible to calculate with considerable accuracy the temperature change at the surface of the earth due to variations in the atmospheric carbon dioxide amount by the use of accurate infrared absorption data analyzed by the modern theory of radiation with the aid of an electronic computor. Previous objections to this theory are based on early, approximate calculations and no longer appear valid.

The carbon dioxide theory can provide simple explanations of most of the known facts about climatic change. Of course, this does not mean that it is the only factor that has influenced the climate. However, it does suggest that it is one of the important factors that must be considered in discussions of climatic change; in many situations it appears to be the determining factor.

The physicist can calculate the temperature change associated with carbon dioxide variations. In order to relate these changes to climatic variations, the carbon dioxide content of the atmosphere for past epochs should be known. In order to determine these variations we must collect evidence from such diverse fields as geology, oceanography, biology, and meteorology. Often we can only guess at which one of the many factors that influence the carbon dioxide balance may have changed in a given geological epoch. Regardless of our uncertainties in this respect, we can be sure that the atmospheric carbon dioxide amount has changed many times and by large factors during the geologic history of the earth and that these variations have had their influence on the climate.