Man-made Carbon Dioxide and the "Greenhouse" Effect

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In spite of the enormous mass of the atmosphere and the very large energies involved in the weather systems which produce our climate, it is being realized that human activities are approaching a scale at which they cannot be completely ignored as possible contributors to climate and climatic change.

THE first thing that has to be recognized is that significant effects on the climate are only likely where human activity impinges on a particularly sensitive factor among those that control climate. The output of human industry is still very much less than the total mass of the atmosphere and man-made energy is still small compared with the energy of meteorological systems. The total industrial output of heat each day is, for example, considerably less than 0.1% of the total kinetic energy of the atmosphere, which itself is destroyed by friction and replaced naturally within a few days. Another useful comparison is that of the total man-made heat output in Britain with natural processes over the same area. Even over this area of relatively intense human activity man's efforts are relatively quite small—man-made heat is less than 1% of the energy received from the Sun.

It must also be remembered that the mass of the atmosphere is enormous compared with the products of human activity. The total mass of the atmosphere is more than 500 times the mass of the known coal reserves, for example, and human activities will not significantly change its chief constituents. Nevertheless there are certain minor constituents of the atmosphere which have a particularly significant effect in determining the world climate. They do this by their influence on the transmission of heat through the atmosphere by radiation. Carbon dioxide, water vapour and ozone all play such a role, and the quantities of these substances are not so much greater than the products of human endeavour that the possibilities of man-made influences can be dismissed out of hand.

Influence of CO_2

This article is concerned with the part played by carbon dioxide in determining climate and the way in which it may be affected by human activity. There are several other possible ways in which man might affect climate on a global scale, but the carbon dioxide effect is probably the one about which the most is known, and at the same time it illustrates clearly the inherent difficulties in assessing whether such activity can have a significant effect on climate and how much that effect might be.

First, it is necessary to consider the natural behaviour of carbon dioxide in the atmosphere and the evidence for changes produced by human activity. Carbon dioxide is, of course, a product of the combustion of nearly all fuels and is discharged to the atmosphere through the chimneys or exhaust of the power or heating plant in which the fuel is consumed. The carbon dioxide content of the atmosphere was first measured in the earlier part of the nineteenth century and found to be fairly uniform, both geographically and with season. By the earlier part of the century it had been pointed out that the combustion of fossil fuel was discharging carbon dioxide, which might be increasing the carbon dioxide content of the atmosphere, and which might have an effect on the heat balance of the Earth. The nineteenth century measurements of carbon dioxide were naturally of a somewhat uncertain accuracy, but by comparison with more recent observations Callendar[1] was able to demonstrate that there is reasonable evidence for an increase attributable to the carbon dioxide added to the atmosphere from the burning of fuel.

The reality of this increase has been confirmed in a remarkable way in the past decade by two series of measurements made at two locations specially chosen to be far away from local sources of pollution. These were at the South Pole and on the summit of the volcanic mountain Mauna Loa in Hawaii. Fig. 1 (taken from ref. 2) shows the trend of carbon dioxide concentration over the past ten years or so at Mauna Loa. The upward trend is apparent, but the diagram also illustrates some other aspects of the problem. The upward trend at the South Pole is closely similar to that at Mauna Loa.

The upward trend amounts to about 0.7 parts per million (p.p.m.) by volume per year over the eleven year period. The value of 312 p.p.m. in 1958 rising to 319 p.p.m. by 1969 compares with the value of around 292 p.p.m. measured by observers in the nineteenth century. Fig. 1 also shows a marked annual fluctuation, emphasizing that carbon dioxide is essential to the growth of vegetation, and is taken up by plants as they grow. (Some is then returned to the atmosphere when they rot and some incorporated in humus, only to be subsequently returned to the atmosphere.) The annual fluctuation in the concentration of carbon dioxide arises because plant growth is greater in the northern hemisphere than in the southern hemisphere (where the land mass is smaller) and plant growth and the uptake of CO_2 is thus a maximum in the northern summer. The carbon dioxide content of the atmosphere is a maximum in the northern spring and a minimum in the northern autumn.

Fig. 1 also shows the rate at which the concentration of CO_2 would have increased if all the man-made carbon dioxide had remained in the atmosphere. The observed increase is only about half of this, the remainder has clearly been removed from the atmosphere by natural processes, and an assessment of the future rise in carbon dioxide content requires a knowledge of what the processes are and where the carbon dioxide is going

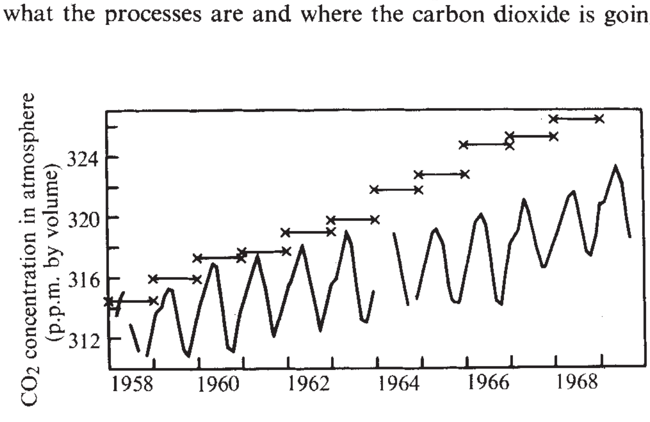

Fig. 1 Increase in carbon dioxide concentration from burning of fossil fuels. ——, Mean monthly atmospheric CO_2 concentration at Mauna Loa; ×—×, potential annual increase from burning fossil fuels. (Reproduced from ref. 2.)

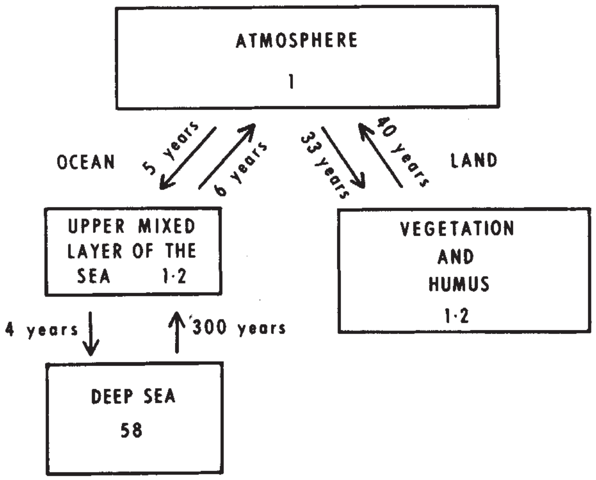

Fig. 2 Natural reservoirs of carbon dioxide (based on ref. 3). Figures indicate content as multiples of atmospheric content.

to. There is also a suggestion in Fig. 1 that the rate of increase of carbon dioxide was rather slower in the mid-1960s than before and after—an indication that these natural processes may vary in their effectiveness from time to time.

Storage and Reservoirs

Fig. 2, which is based on a diagram due to Craig[3], shows the natural reservoirs of the carbon which takes part in the carbon dioxide cycle and the relative size of these reservoirs. On land the carbon dioxide is taken up by vegetation and stored in plants and humus. This reservoir is of similar magnitude to that of the atmosphere, and the exchange time is probably of the order of 30 to 40 yr. The ocean provides a much larger reservoir and has the potential for storing some sixty times as much carbon dioxide as the atmosphere. The upper layers of the sea (above the thermocline) must, however, be distinguished from the deeper layers of the ocean. The upper layers are well mixed, and are in contact with the atmosphere, but they can hold only about as much carbon dioxide as exists in the atmosphere. Studies of the concentration of ^{14}C, which is produced by cosmic rays in the atmosphere and subsequently decays to ^{12}C, suggest that the rate of transfer of carbon dioxide from the atmosphere to the upper layers of the ocean is such as to require some 5 to 10 yr for the transfer of a quantity equivalent to that in the atmosphere. Transfer to the deep ocean from the upper layers is a slower process, and as a result it would be a matter of centuries before the deep ocean reached equilibrium with any new level of concentration in the atmosphere.

Industrial development has recently been proceeding at an increasing rate so that the output of man-made carbon dioxide has been increasing more or less exponentially. So long as the carbon dioxide output continues to increase exponentially, it is reasonable to assume that about the same proportion as at present (about half) will remain in the atmosphere and about the same amount will go into the other reservoirs. On this basis Bolin[4] has estimated that the concentration of carbon dioxide will be about 400 p.p.m. by the year 2000. A recent conference[5] put the figure somewhat lower (375 p.p.m.)

On the other hand, there must ultimately be a levelling off in industrial output of carbon dioxide, if only on account of the limitations of fuel supply. At this stage a larger proportion of the carbon dioxide will be absorbed by the oceans because, on the longer time scale, the deep sea will have opportunity to come nearer to equilibrium with the atmosphere. If the carbon dioxide were to be shared between the various reservoirs in proportion to their capacities, only one-sixtieth of the man-made carbon dioxide would remain in the atmosphere—but unfortunately the situation is more complex than that.

Chemical Complications

Kanwisher[6] has pointed out that only a small proportion of the carbon dioxide entering the sea remains as dissolved CO_2 directly available for exchange with the atmosphere. The remainder forms magnesium and sodium carbonates which provide a chemical buffering solution for carbon dioxide. In consequence an increase of 0.6% in the carbon dioxide content of the sea corresponds to a 10% increase in the partial pressure of CO_2 in the atmosphere above, and on this basis one might expect that the ultimate sharing of carbon dioxide between the atmosphere and the whole ocean might still leave more than 20% of the extra carbon dioxide in the atmosphere. On a still longer time scale one might expect some of the oceanic carbon to be deposited as carbonates on the sea bed, but the typical times associated with this process is probably too long to be of much relevance to the fate of industrially produced CO_2.

There is little doubt that in assessing the future level of carbon dioxide in the atmosphere, it is important to understand fully the balance between the carbon dioxide in the atmosphere and in the ocean. There are several other complications which are not fully understood. The solubility of carbon dioxide is greater at lower temperatures and the tropical oceans are thus continuously giving up carbon dioxide to the atmosphere; it is then reabsorbed in the oceans of higher latitudes. In most parts of the ocean there is a relatively warm layer of water lying above colder and denser water beneath—the transition layer, known as the thermocline, lies at a depth of 100 to 200 m. This stable layer is a barrier to the mixing of the lower and upper water of the ocean, but the barrier disappears in certain parts of the polar ocean when the surface water is cooled in winter, and such areas may provide a pathway by which carbon dioxide absorbed from the atmosphere can be transferred to the deep ocean more readily. Such areas may play a significant role in determining the carbon dioxide balance between ocean and atmosphere, and an understanding of this balance will require a better understanding of the long term circulation of the ocean than is available at present.

Indirect Effects of Increased CO_2

The direct effect of a small increase in carbon dioxide on mankind would be negligible (except that it might make some vegetation grow a little faster) and I shall now consider its possible indirect effect on the world climate.

The temperature of the Earth is, of course, maintained by the energy received from the Sun as radiation in a band of wavelengths centred in the visible region. Some of this radiation is reflected by the Earth's surface, and more especially by clouds, but most of the remainder penetrates the atmosphere and heats the Earth's surface including the ocean. Some of the heat is radiated back by the surface at longer wavelengths corresponding to its lower temperature than the Sun, part is communicated to the overlying air by conduction, and part is used to evaporate water and becomes available to heat the air when the water condenses as rain. The atmosphere is not transparent to the long wavelength radiation which is emitted by the Earth and its atmosphere, as it is to the incoming short wave radiation. Thus certain atmospheric gases, principally water vapour and carbon dioxide, absorb a significant part of the outgoing radiation and reradiate it both upwards and downwards. (The significant aspects of the radiation spectrum are illustrated in Fig. 3.) The outgoing radiation from the Earth-atmosphere system is thus made up of, first, some radiation emitted by the Earth's surface at wavelengths to which the Earth's atmosphere is transparent—the so-called "window", primarily between 7 and 14 μm; second, some radiation which has been emitted from the surface (or from clouds), absorbed by atmospheric gases and reradiated outward by the same (or other) gases; and, third, radiation from clouds which themselves may be receiving heat from below. Some of the heat radiated outward by the gases and clouds is transported from below to the level where it is radiated. These aspects of the radiation balance of the atmosphere are illustrated in Fig. 4.

As carbon dioxide is one of the principal gases taking part in radiation exchange in the atmosphere and in the radiation of the Earth's heat content, a change in the content of carbon dioxide within the atmosphere is likely to influence the process. The chief effect of increasing carbon dioxide is that the gas which is radiating heat to space is found at a higher level in the atmosphere than before—the radiation from lower down in the atmosphere is absorbed by the extra carbon dioxide above and then reradiated to space. In the troposphere, at least, temperature decreases with height, so the effective radiating temperature of the carbon dioxide becomes lower if the amount of the gas is increased, and therefore less heat is radiated to space. Thus the additional carbon dioxide tends to act as a blanket which keeps the Earth warmer—the Earth has to get rid of the incoming radiation from the Sun, and the same amount can only be removed if the temperature of the atmosphere rises a little.

The calculation of the effect on the radiation budget is not easy because the absorption and emission of heat through the whole of the long and short wave radiation spectum has to be taken into account, and the heat transfer has to be calculated by integration over the very complicated spectrum resulting from the complex pattern of absorption bands introduced by the various atmospheric constituents. Neverthless modern computing resources allow reasonably accurate computations to be made. Probably the most reliable calculations performed so far are those reported by Manabe and Wetherald[7], who point out and overcome two important deficiencies of earlier calculations. The deficiencies arise, first, because the vertical distribution of temperature in the atmosphere is not determined by radiation transfer alone; and, second, because, if world temperature rises due to an increase in carbon dioxide, it is almost certain that there will be more evaporation of water—the water vapour content of the atmosphere will also increase and will have its own effect on the radiation balance.

The first difficulty is overcome by incorporating a restriction in the calculations, namely, that the temperature must not fall off more rapidly with height than $-6.5°$ C km^{-1}, the rate normally found in the troposphere. If this rate is exceeded during the calculations a so-called "convective adjustment" is made.

The second effect is probably more important in the present context. An atmosphere at a higher temperature can hold more water vapour, and the additional water vapour produces a similar blanketing effect to that produced by carbon dioxide. Manabe and Wetherald[7] calculate that an increase of 100% in the content of carbon dioxide would increase the world temperature by 1.3° C if the water content of the atmosphere remained constant, but by 2.4° C if the water vapour increased to retain the same relative humidity. The increase of 25% in CO_2 expected by the end of the century therefore corresponds to an increase of 0.6° C in world temperature—an amount somewhat greater than the climatic variations of recent centuries. Rasool and Schneider[8] give a more recent and substantially smaller estimate of the effect of carbon dioxide, but their scheme makes no allowance for adjustments of stratospheric temperature or absorption of incoming radiation by carbon dioxide.

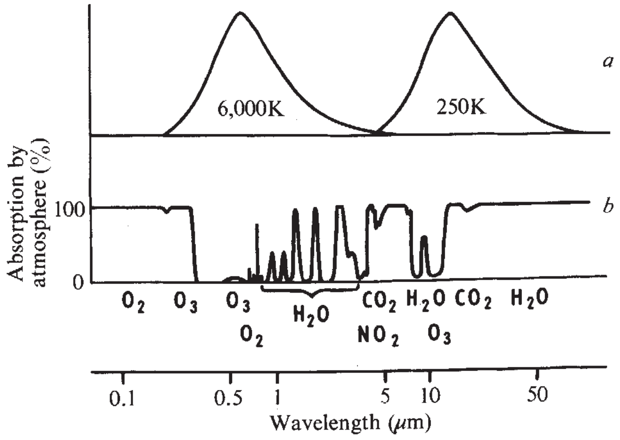

Fig. 3 Radiation spectrum illustrating absorption by principal atmospheric absorbing gases. *a*, Black body curves; *b*, absorption by atmosphere.

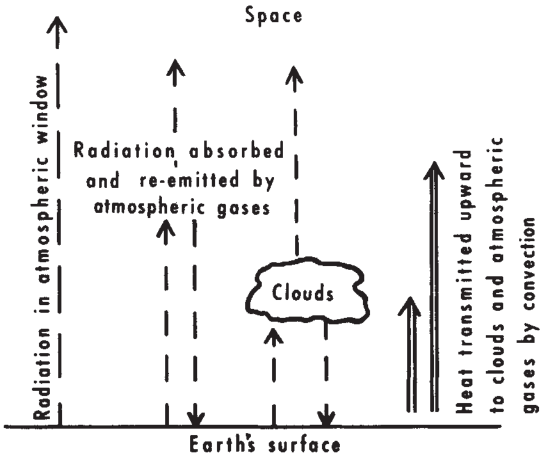

Fig. 4 Pathways of heat loss from the Earth and atmosphere.

Other Variables

The water vapour content is by no means the only variable factor in the atmosphere which would change as a result of a general warming. The increased water vapour would probably lead to the formation of more clouds because evaporation increases much faster than temperature, and substantially more condensed water would be available. The additional cloud would reflect incoming solar radiation and tend to produce a lowering of temperature—a negative feedback effect to counterbalance the positive feedback arising from water vapour. Other calculations[7] show that world temperature is likely to be remarkably sensitive to the average global cloudiness. A change of only 1% in the average cloudiness would produce a change in temperature of almost 1° C. As cloudiness varies greatly from day to day and from place to place, it is really rather remarkable that the fluctuations in world temperature are not greater than those observed. There is thus a suggestion that the negative feedback from cloud cover is a real stabilizing effect on world temperature, increasing cloud keeping the temperature down and cutting off evaporation until the average cloudiness is restored. No quantitative estimate of this effect has, however, yet been made.

On the other hand, a destabilizing feedback which has been given some prominence recently arises from the changes in the Earth's reflectivity which would accompany any change in its permanent cover of ice and snow. A lowering of temperature would lead to an extension of glaciers and permanent snow fields, and these would reflect more of the incoming solar radiation. Budyko[9] has stressed the destabilizing influence of such positive feedback and has suggested that a decrease of incoming solar radiation of only about 2% might lead to another ice age and indeed to complete glaciation of the Earth. The effect of the decrease of ice cover which would accompany an increase of world temperature is, however, less significant. The present limits of permanent snow and ice are such that no extensive recession is possible with increasing temperature without a thawing of the ice cover of the Arctic Ocean. If this took place it would undoubtedly have a significant effect on the climate of the adjacent coasts and hinterland, but the indications are that the effect on the mean temperature in other latitudes would be limited to 1° or 2° C. Regional climatic effects might, however be significant.

The oceans also have an influence on climatic changes through their large mass and thermal inertia. The atmosphere cannot settle down to a new temperature regime until the temperature of the oceans has come into equilibrium with that regime. Calculations show that this would take of the order of 100 yr, and in consequence the oceans impose a substantial lag on the response of world temperature to such changes as I have discussed here. On the other hand, a rise in temperature of the oceans will itself release additional carbon dioxide to the atmosphere and provide a positive feedback tending to enhance slightly the carbon dioxide effect.

The response of the atmosphere to a change in its heat balance is far from simple. Almost any change in the heat supply is likely to result not only in a change in the overall temperature, but also in the system of winds and weather which derive their energy from the heating and cooling of the atmosphere. Such a change in the winds produces of itself a change in climate, and also modifies the cloud and temperature distribution with a possible feedback to the heat supply and heat loss by radiation.

In spite of the enormous complications of attempting to calculate the whole circulation of atmospheric winds and the resulting cloud and rain distributions, it is probable that only in this way can a soundly based estimate of possible man-made climatic changes be made. Numerical models of the atmospheric circulation have been developed and the computations are just practicable on the largest modern computers. The calculations reproduce the chief features of the world climate, but do not have sufficient precision to differentiate two regimes which would produce a difference of temperature of 1° or 2° C. Possibly such calculations will be feasible in the future, but the sophisticated models required will have to take into account the complicated feedback processes which I have already discussed. Most difficult is to devise a method of calculating the amount of cloud to be expected in a particular circulation regime because individual clouds are too small to be treated; the statistical behaviour of assemblies of clouds covering a region will have to be calculated, and it is not yet clear how this may be achieved.

Possible Changes and Natural Fluctuations

The climate has undergone many changes in the past. Some of these have been associated with the formation of the atmosphere itself, the generation of oxygen by vegetation and so on, but large scale geographical changes, the moving of the continents, have also played a part. Even since geography and atmospheric composition have been more or less as they are known at present, there have been ice ages and periods considerably milder than the present—the causes of these changes are unknown. The last ice age came to an end over a period of centuries about 10,000 yr ago, but even since then there have been changes. Since the temperature recovered to more or less current values the climatic fluctuation in England has at most been a matter of 2° C or so. The biggest swing in recent decades has probably been about 1° C from the medieval optimum to the little ice age around the seventeenth century. Individual years, even in the past two decades or so, have, however, covered a wider range than 2° C. Even global mean temperatures have varied by 0.6° C from a minimum around 1880 to the last maximum around 1940. Against this background a change of 0.6° C by the end of the century will not be easy to distinguish from natural fluctuations and certainly is not a cause for alarm. Even a doubling of the amount of carbon dioxide in the atmosphere, which would probably require the burning of a large part of the known fuel reserves, would appear to result in a rise of temperature little above that experienced in the climatic optimum which followed the last ice age. Nevertheless it must not be overlooked that variations in climate of only a fraction of a degree centigrade have considerable economic importance, as experience of natural fluctuations has already shown. The more frequent incidence of severe winters or of frost can readily affect the economies of sensitive crops.

Although there may be no immediate cause for alarm about the consequences of carbon dioxide increase in the atmosphere, there is certainly need for further study. We need to have a better assessment of where the carbon dioxide goes after it has been dispersed from our chimneys, and in particular the long term balance with the ocean. We also need a better assessment of the various feedback effects which enter into the control of climate, and the development of increasingly sophisticated numerical simulation of the global climate seems the only possible approach in spite of the effort involved.

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Progress Maintained in Molecular Biology

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Although progress in molecular biology may be slowing down somewhat, an account of recent developments inevitably involves some selection.

SUFFICIENT important developments have occurred in molecular biology during the past year to make it difficult to review the subject comprehensively in an article such as this. The selection that has occurred is bound to reflect personal interest, but the topics discussed here probably comprise the more important achievements of the past year, together with those lines of experimentation that seem most likely to lead to interesting results.

The determination of the complete nucleotide sequence of a structural gene represents a most impressive technical achievement by Fiers and his group in Ghent; they have reported the