CAN CARBON DIOXIDE INFLUENCE CLIMATE ?

By G. S. Callendar

An interpretation of climatic change in terms of the variable carbon dioxide content of the atmosphere was first proposed some sixty years ago by the famous Swedish physicist, Sevante Arrhenius, who made some of the classic experiments on the absorption of heat radiation by gases. Since then the theory has had a chequered history ; it was abandoned for many years when the preponderating influence of water vapour radiation in the lower atmosphere was first discovered, but was revived again a few years ago when more accurate measurements of the water vapour spectrum became available.

Reduced to its simplest terms this theory depends on the fact that, whereas carbon dioxide is almost completely transparent to solar radiation, it is partially opaque to the heat which is radiated back to space from the earth. In this way it acts as a heat trap, allowing the temperature near the earth's surface to rise above the level it would attain if there were no carbon dioxide in the air. Two other gases in the atmosphere, water vapour and ozone, also possess this property of returning back towards the surface some of the low-temperature radiation which would otherwise escape directly to space. The former is present in such large quantities over most of the earth's surface that it plays by far the most important part in the radiation of the lower atmosphere.

It is mainly owing to the predominance of water vapour and the extreme irregularity of its absorption that attempts to assess the effect of carbon dioxide on temperatures have so far met with little success. Even in the laboratory the absorption of radiation by water vapour has proved an exceedingly difficult measurement, and after eighty years of experiments agreement is by no means complete. Carbon dioxide, however, has a simpler and more restricted spectrum and fair agreement has been attained for this gas (*Quart. J.R.Met. Soc.*, Vol. 67, 1941, p. 263).

In the present state of knowledge it seems probable that the change in temperature as a result of variations in carbon dioxide can best be evaluated by comparing the earth to a body receiving a constant supply of heat which is dissipated by radiation through a surrounding medium. Then it can be shown that

$$\frac{dT}{dE} = \frac{T}{4-4E}$$

where T is the temperature of the surface, and E is the emissivity of the surrounding medium towards the surface.

Changes in the amount of carbon dioxide affect the emissivity of the atmosphere at all levels, including the downward component at the surface, and these effects can be calculated with some accuracy from the known absorption coefficients. For example it is found that, with a temperature of 280° A and a downward emissivity of 0·70, a change to double the present amount of carbon dioxide in the atmosphere should increase E by 1·3 per cent, equal to a temperature rise of 2·1° C (3·8° F) so long as it caused no interference with the heat supply to the surface. Such calculations would occupy too much space to elaborate here.

WHERE THE EFFECT OF CARBON DIOXIDE IS GREATEST

In considering the regions where variations in the amount of carbon dioxide will have most effect on the balance of heat-exchange, one naturally turns to those where the temperature is very low and the importance of water-vapour radiation is reduced ; but there are many low-lying regions of intense cold in the northern winter where the surface heat-loss is small and unimportant because there is little heat-supply from the stagnant air. The active regions of heat-loss in very cold air generally occur at higher levels in the atmosphere, or on elevated land masses such as Central Asia and the Antarctic Continent.

As an example of the former, the heavy convectional rainfall of the tropics depends very much upon the speed at which the middle and upper troposphere can rid itself of the heat energy which is constantly being sent up from below, mainly as the latent heat of water condensation. This heat is radiated away through the thin cold air of the stratosphere, in these regions almost devoid of the protecting layers of water-vapour. It contains, however, the usual proportions of carbon dioxide, in optical densities such that small changes have a relatively large effect on its absorption of radiation from below. Thus an increase of carbon dioxide could reduce the rate of heat-loss from the upper troposphere, which in turn could reduce the vigour of the convection currents and the rainfall, or, alternatively, allow surface temperatures to rise until a new balance was reached. An increase in the aridity of marginal tropical regions and a recession of the glaciers on high tropical mountains might be one of the first indications of this.

Another area of active heat-loss where changes of carbon dioxide could be very important is the upper surface of clouds. This area is vast and its loss of heat often occurs through very dry layers of the atmosphere ; thus, increase of carbon dioxide would mean slower cooling of clouds, perhaps accompanied by less persistent cloud cover and more effective solar heating at low levels.

In the great polar ice caps, where temperatures are very low, and yet for dynamical reasons the rate of heat loss is quite high, the effect of changes of carbon dioxide is doubtless more complex, although we might expect some temperature adjustment to balance the change of emissivity. Whether this temperature adjustment had any effect on convectional processes would depend on its difference from changes elsewhere in the atmosphere. There are many other effects which might be attributed to changes in the amount of carbon dioxide, but enough has been said to indicate where they are most likely to have some influence on world temperatures. The next step is to examine the possibility of such changes being brought about by human agency.

Although those who have studied radiation in the atmosphere will agree that variations of carbon dioxide could have significant effects in the regions just mentioned, they may be doubtful of the possibility of such variations being caused by human activities. For instance, we know that the green parts of plants use this gas to build up their structure, that sea-water can absorb it, that limestone is partially composed of it, and so on. These are all factors in the natural carbon cycle which has been so ably treated by Lundegath (*Der Kreislauf der Kohlensaure in der Natur*, Jena, 1924), Quinn and Jones (*Carbon Dioxide*, Reinhold, 1945) and several others ; but it is not possible to examine these factors here, beyond stating that they are part of a balance maintaining a fairly constant amount of this gas in the air.

It is only during the present century that man has exerted his influence on a sufficient scale to disturb nature's slow-moving carbon-balance, but now his demand for heat and power has led to the transfer of large quantities of " fossil " carbon from the rocks to the air. As one ton of coal or oil produces about three tons of carbon dioxide it is a simple matter to estimate the quantity of the latter derived from the known output of these fuels. This is now about 5,000 million tons per year. One part per million by volume (p.p.m.) in the whole atmosphere is equal to 8,000 million tons of carbon dioxide, the change in the latter over the years may be obtained and compared with the most reliable measurements as in Table 1.

Table 1.—Estimated effect of fuel combustion on atmospheric CO_2

Date	CO_2 from fuel as p.p.m.	Total air CO_2 p.p.m.	Observed value		
			Date	Authority	p.p.m.
to 1900	Small	290	1870–1900	Numerous (*a*)	290
1901–10	3	293	1910	Benedict (*a*)	303
1911–20	5	298	1922	Lundegath (*b*)	305
1921–30	5·5	303	1931	Carpenter (*c*)	310
1931–40	6	310	1935	Buch (*a*)	320
1941–50	6·5	316	—	—	—

Refs. : (*a*) See Callendar, 1940 *Quart. J.R. Met. Soc.*, Vol. 66, p. 395.
(*b*) *loc. cit.*
(*c*) 1937 *J. Amer. Chem. Soc.*, Vol. 59, p. 323.

The observed values in Table 1 appear to indicate a more rapid increase of carbon dioxide than that from fuel alone, but there are several other ways in which man's activities release this gas to the atmosphere in amounts reckoned in thousands of millions of tons ; chief among these are the clearance of forests and the drainage and cultivation of land, by which immense quantities of organic residues are exposed to bacterial oxidation. There is, however, no need for alarm at the possibility of the air becoming contaminated by too much carbon dioxide, because the waters of the oceans provide a reservoir of almost infinite capacity to absorb excess. As the deep waters of the sea move slowly and only a shallow contact surface is involved in the carbon-dioxide equilibrium, this reservoir does not immediately control a sudden eruption of the gas such as has occurred this century. It will be hundreds or perhaps thousands of years before the sea absorbs its fair share.

Similarly it is possible for the percentage of carbon dioxide to vary considerably in periods of only a few centuries when some exceptional event absorbs large quantities. An example of this is the recolonization of continental areas by forests and peat at the close of the last glaciation.

THE PRESENT TREND OF CLIMATE

It will be seen from the foregoing that the amount of carbon dioxide in the atmosphere may be increased significantly by human activities ; and that there are reasons to expect some slight amelioration in climate to follow from the increase. Hence we may now consider whether the thermometer already shows signs of rising in synchronization with the increasing thickness of the carbon-dioxide radiation blanket, remembering that only very small changes of temperature are expected to occur in periods of a few decades, and that the pitfalls which await the uncritical who venture into this field are numerous. There remain, however, a fair number of temperature records from different parts of the world, of over half a century's duration, which will stand critical analysis both as regards accuracy and the stability of surrounding conditions.

Examination of the trend of mean temperature given by these long records shows that it has been upward during the last half-century in nearly all cases. A few typical figures (Table 2) indicate the order of the temperature rise over this period, as deviations in successive twenty-year means. Some attempt at random selection has been made by taking half the stations under the letter B which have the necessary length of record, and also a wide distribution over the earth.

Table 2.—The trend of temperature in various regions.

20-year deviations from the mean for 1880–1899, in tenths of a degree Fahrenheit.

20 years ending	Britain	Bergen	Boise	Bombay	Batavia	Buenos Aires
1909	3	0	6	3	3	2
1919	3	1	11	5	5	3
1929	4	3	10	7	7	4
1939	7	10	17	7	11	9
1948	10	—	—	—	—	—

Naturally, one would have to go into the history of these observations, comparing them with neighbouring rural sites and so on, before accepting the figures at their face value ; but, without going into details, it may be said that any other half-dozen stations selected at random from widely-scattered regions would show much the same average change of temperature as those given. In marginal sub-arctic regions changes three or four times as great have occurred in the last few decades, but here advectional influences are of paramount importance.

The variations of glaciers, often located in regions where there are no reliable temperature records of long duration, are perhaps even more significant of climatic change than the instrumental readings with their possibility of human error. That they have lately been receding in most parts of the world is well known ; recent evidence of this from the southern Andes and New Zealand is specially valuable, because of the lack of old temperature records in the southern hemisphere which can be said to be free from urban influence.

Naturally one would expect any change of climate due to variations in the atmospheric radiation to be world wide in its effects, although there is much doubt as to their nature in a region such as the Antarctic continent, where temperatures are below freezing point at all seasons. In fact, an increase in the amount of ice here might be the ultimate result of higher world temperatures. But in a short article such as this it is only possible to consider the broad outlines of the probable effect of carbon dioxide on climates, and we must be content to leave many of the problems associated with it for future research.

In conclusion it may be said that the climates of the world are behaving in a manner which suggests that slightly more solar heat is being retained in the atmosphere. This could be due to its increasing opacity to terrestrial heat as a result of the additions of carbon dioxide. But the coincidence by itself is no proof, because we do not know if the solar heat has remained constant over the period ; it does, however, provide an intriguing example where the expected happens on the grand scale.

METEOROLOGY IN GRAMMAR SCHOOLS

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The Royal Meteorological Society, keenly aware of the instructional needs of the science which it sponsors, has always encouraged the formulation of schemes and the publication of informed opinion on the teaching of meteorology. The last article on the subject in its publications having appeared in 1931, the time is now opportune to review the question again. The weather being one of the most profound influences on mankind, there is a good case for making the study of it an important part of a curriculum, or at any rate, giving it more prominence than it has enjoyed hitherto. With the widening of man's activity in earth and sea and sky, the influence of the weather becomes a correspondingly greater factor and hence a wider understanding of its principles is desirable ; in this connection it is worth noting that among the Ministry of Education vacation courses planned for 1949 the science course in Norway includes meteorology. The teaching of the subject in schools is easier nowadays than ever before ; there is an increase in the number of teachers in schools with training in meteorology, many being ex-service meteorological personnel ; again, synoptic data are now readily available. This article is an expression of the writer's personal opinion on the question of teaching meteorology in Grammar Schools, most of the