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Greenhouse Effects of Some Atmospheric Constituents

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Greenhouse effects of some atmospheric constituents

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The present state of our knowledge of the greenhouse effect is discussed and the limitations of existing atmospheric models that are used to predict changes in the greenhouse effect are pointed out. In particular the possibly dominant effect of the cloud/radiation feedback process is mentioned. Current models predict about a 2 K rise in surface temperature for a doubling of the atmospheric CO_2 concentration and a 6 K rise if the CO_2 increased by a factor of 8 as is possible in the future if the increase in the burning of fossil fuels continues. Possible greenhouse effects due to the release of chlorofluoromethanes (c.f.ms) and aerosols into the atmosphere from man-made sources are small. Analysis of the surface temperature changes which have occurred in the Northern Hemisphere during the last 100 years are consistent with most of the changes being due to increased CO_2 and decreased stratospheric aerosol.

1. The greenhouse effect

In the absence of clouds the Earth's atmosphere is largely transparent to solar radiation but mainly opaque to infrared radiation (figure 1). Because much of the radiation in the infrared emitted by the Earth's surface is trapped by the atmosphere, the temperature of the Earth's surface is substantially raised. This mechanism is known as the greenhouse effect. The name arises because the same mechanism occurs in glass greenhouses, glass being largely transparent to solar radiation while absorbing completely radiation in the infrared beyond about 3 μm in wavelength. Although the more important function of a greenhouse is to reduce the circulation of air, rather than to trap the infrared radiation (as is for instance exemplified by the effectiveness of greenhouses made of polythene which is transparent in the infrared as well as the visible), the name greenhouse effect continues to be used.

The greenhouse effect can be enhanced if the concentration of constituents which absorb in the infrared is increased. The constituents that I shall discuss in this paper are (1) carbon dioxide, (2) minor constituents such as the chlorofluoromethanes (c.f.ms) which possess absorption bands in the 10–12 μm atmospheric window where there is relatively little absorption by other constituents, and (3) aerosol.

2. Carbon dioxide

Carbon dioxide is the main absorber of atmospheric radiation in the 13–18 μm wavelength region – a region near the peak of energy distribution for black bodies near terrestrial temperatures (figure 1). Because of the burning of fossil fuels the concentration of carbon dioxide in the atmosphere has been increasing and will increase more rapidly in the future as the world consumption of fossil fuels accelerates. The mean concentration of CO_2 in the atmosphere measured at Mauna Loa, Hawaii, is currently (1977) 329 parts/10^6 by volume and is rising at about 0.9 parts/10^6 per year. (Peterson *et al.* 1977.) Before industrialization its concentration is estimated as having been around 280 parts/10^6, which implies that about half of the carbon dioxide resulting from normal activities has remained in the atmosphere (*Inadvertent climate modification*

1971). By the year 2000 the CO_2 concentration is expected to rise to 380 parts/10^6, and on the assumption that most of the known world's supply of fossil fuels are burnt by the end of the twenty-second century, the amount of carbon dioxide in the atmosphere could rise by a factor of between 4 and 8 above the present amount (National Research Council 1977). This latter prediction is very uncertain because of our current lack of knowledge concerning the rate at which CO_2 is exchanged between atmosphere and ocean and because we have only very poor information about the changes which are occurring or which may occur in the carbon content of the biosphere (Bolin 1975).

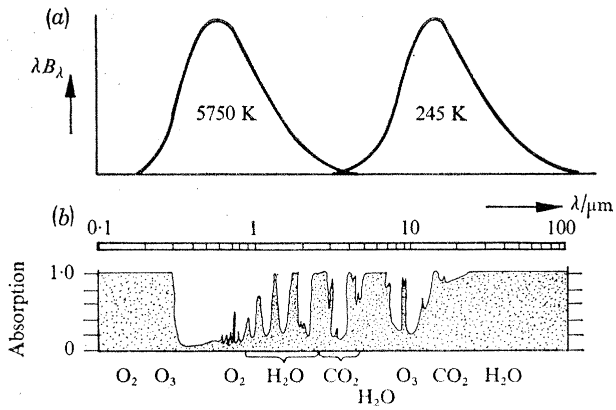

FIGURE 1. (a) Curves of black-body energy B_λ at wavelength λ for 5750 K (approximating to the Sun's temperature) and 245 K (approximating to the atmosphere's mean temperature). The curves have been drawn of equal areas since integrated over the Earth's surface and all angles the solar and terrestrial fluxes are equal. (b) Absorption by atmospheric gases for a clear vertical column of atmosphere. The positions of the absorption bands of the main constituents are marked. (From Houghton 1977.)

Since Plass's (1956) modelling study, a number of models have been developed for estimating the effect of increasing atmospheric carbon dioxide on surface temperature. The simplest of these involve calculations of the upward and downward radiation fluxes under some average atmospheric conditions from which a change in equilibrium surface temperature can be deduced following a change in carbon dioxide. More elaborate calculations involve fully developed three-dimensional models. One of the most thorough calculations to date is that by Manabe & Wetherald (1975). The model they employed was fully three-dimensional, and includes horizontal transports, convective adjustment, atmospheric water vapour dependent on surface conditions, and climatological cloud cover. The distribution of temperature change found from their model as a result of doubling the atmospheric CO_2 concentration is shown in figure 2; the average temperature change at the surface is about 2 K. Notice the much larger temperature change that is predicted near the pole, arising from what is known as ice–albedo feedback, i.e. if increased temperature removed some ice from the surface the surface albedo is reduced leading to further heating and increased surface temperature.

This figure of 2 K temperature rise resulting from a doubling of the CO_2 as found by Manabe & Wetherald (1975) is supported by the results of other similar models (see, for example, Schneider (1975) and is the one which is most often quoted. However, it must be pointed out that although these models include many of the relevant physical processes, there are some very fundamental feedback mechanisms (see figure 3) which are not included and for which there are, as yet, no adequate means available for their inclusion. The most important of these is the effect of varying

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cloud cover. In Manabe & Wetherald's model the cloud amount is not allowed to vary interactively with other parameters, whereas in the real atmosphere it depends on the detailed circulation patterns and also may be expected to vary with surface temperature and water vapour concentration. In considering how the surface temperature would vary with changing cloud cover, two competing effects have to be taken into account for an increase in cloud cover,

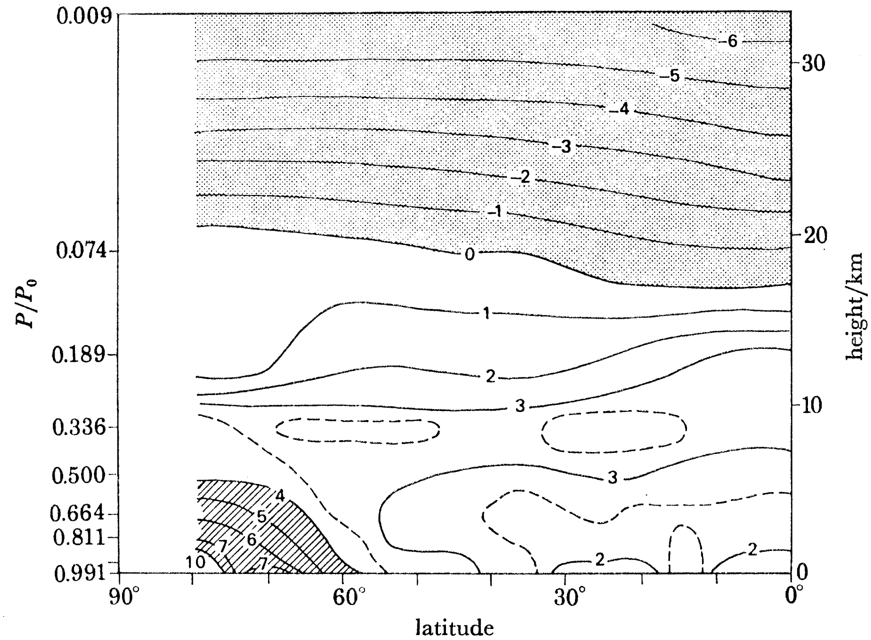

FIGURE 2. Distribution of temperature change (kelvins) resulting from a doubling of the CO_2 concentration as computed in a general circulation model by Manabe & Wetherald (1975).

namely the loss of solar radiation due to the increased albedo and the increased downward infrared flux at the surface. Cess (1976) suggests that the two effects approximately balance each other out, whereas Schneider (1972) finds the albedo effect dominates so that an 8 % increase in cloud cover would reduce the surface temperature on average by about 2 K. Schneider (1972) also points out the importance of cloud-top height (an increase of less than 0.5 km would raise the surface temperature by 2 K) and that the variation of the resultant effect with latitude is quite marked. Of particular importance is likely to be the effect on cloud cover near the pole where the ice–albedo feedback can be so effective. Better observations of the details of the Earth's cloud cover and its variations with space and time are urgently needed so that more adequate methods of incorporating cloud into numerical models can be devised. In the meantime, considerable uncertainty regarding the accuracy of estimates of the effect of increasing CO_2 such as those of Manabe & Wetherald must remain.

The above discussion has centred around the surface temperature changes which would occur with a doubling of the atmospheric CO_2 content. As the CO_2 amount is increased further the response of the surface temperature as estimated by current models is not linear with CO_2 amount (see, for example, Rasool & Schneider 1971) but more nearly logarithmic so that an increase to eight times the present CO_2 concentration would, in these models, result in an average surface temperature rise of around 6 K.

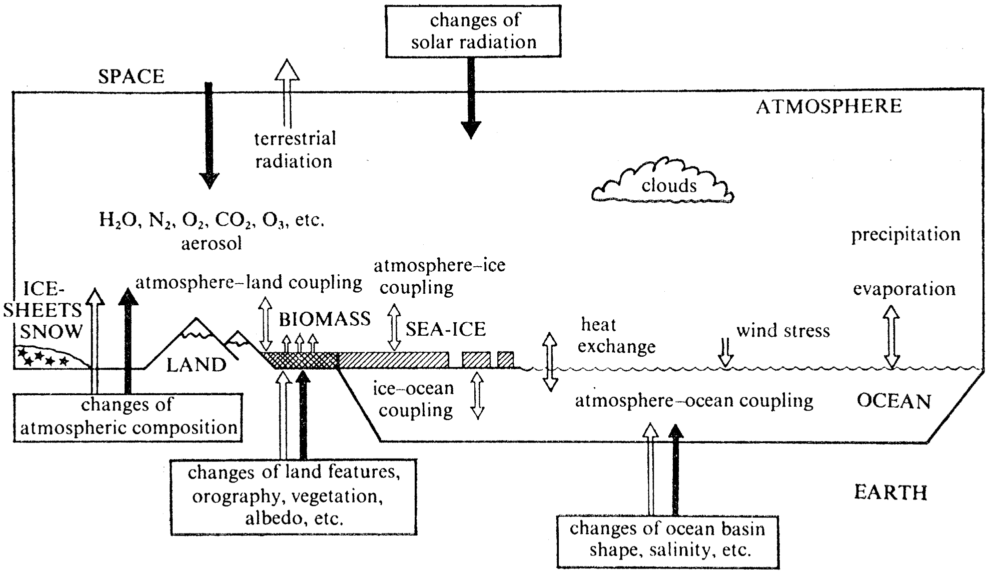

FIGURE 3. Schematic of the components of the coupled atmosphere–ocean–ice–earth climatic system illustrating some of the feedback processes. (From G.A.R.P. 1975.)

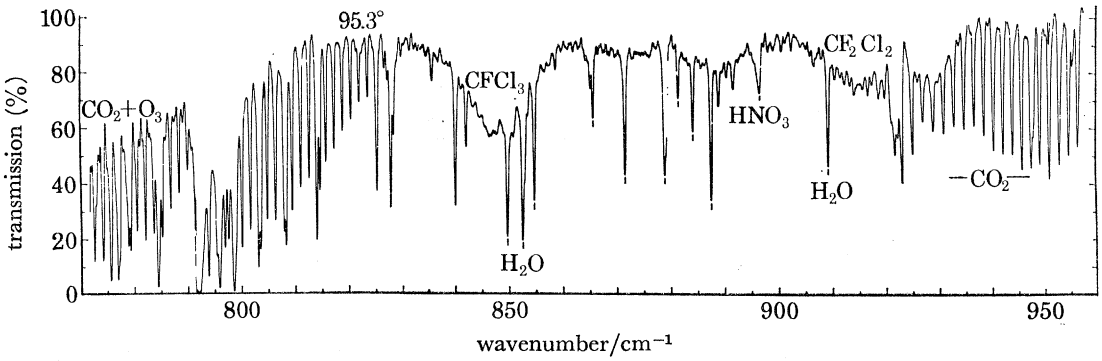

FIGURE 4. Atmospheric transmission in the atmospheric window region observed from a balloon-borne spectrometer from a height of 30 km along a limb path at 95.3° to the zenith by Williams *et al.* (1976). Notice the absorption bands of $CFCl_3$ and CF_2Cl_2. Resolution is 0.2 cm^{-1}.

3. The chlorofluoromethanes

Figure 4 is a record of atmospheric transmission in the atmospheric window region near 11 μm wavelength of a near horizontal path at an altitude of 30 km as measured from a balloon. Absorption bands due to $CFCl_3$ and CF_2Cl_2 can be clearly seen. Although for a vertical path of atmosphere the maximum absorption in these bands is small – less than 0.5 % – because they are in the window regions and near the peak of the energy spectrum for a black-body at terrestrial temperatures, it is possible that the effect on radiative transfer could be significant. Using a simple model, Ramanathan (1975) has calculated that if c.f.ms continue to be released at 1973 rates so that by the year 2000 the tropospheric concentrations were about 0.3 parts/10^6 for $CFCl_3$ and 0.6 parts/10^6 for CF_2Cl_2 (National Research Council 1976), the surface temperature rise would be about 0.2 K which is about half the effect which would arise from increased CO_2 during the same period. This model calculation is, of course, subject to the same assumptions and limitations as those for CO_2 mentioned in § 2.

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4. Aerosols

Particulate matter, mainly originating from the surface, is present in the troposphere where its lifetime is quite short (typically a few days). Tropospheric aerosol plays an important part in determining the heat budget of the surface and atmosphere over large continental areas but may not be very significant so far as changes in the global climate are concerned.

Stratospheric aerosol, on the other hand, has a much longer lifetime (several years) and is spread around the globe so that climate on a global scale may be affected. There are well-defined aerosol layers present near 20 km altitude consisting largely of sulphate particles which are formed as a result of chemical processes in the stratosphere (Toon & Pollack 1973). Other sources of stratospheric aerosol are volcanoes (which may in addition produce the SO_2 for the sulphate chemistry) and debris from meteor showers.

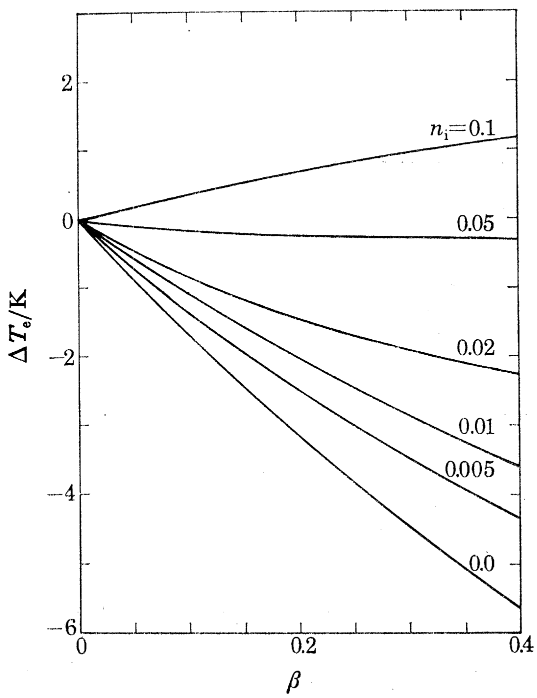

Figure 5. Change in surface temperature, ΔT_e, arising from different atmospheric aerosol contents as calculated by Yamamoto & Tanaka (1972); β is the turbidity factor and n_i the imaginary part of the refractive index of the particles.

The effects of stratospheric aerosol on the atmosphere's radiation budget arise from the same two reasons as those due to clouds mentioned in § 2. Yamamoto & Tanaka (1972) have made a detailed study of scattering and absorption of solar and infrared radiation by a layer of aerosol. The size of the resulting change in surface temperature and even whether it is positive or negative depends on the imaginary part n_i of the refractive index of the particles (figure 5). Typical values of n_i for stratospheric particles are 0.01 or less (Toon & Pollack 1976) so that cooling rather than heating can be expected to result from an increase in optical thickness of the stratospheric aerosol layer. By way of illustration, a situation of increased aerosol following the eruption of the volcano Fuego in October 1974 can be considered; it has been studied in some detail by Russell & Hake (1977). A typical optical thickness for the mid visible part of the spectrum of the stratospheric

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aerosol in a vertical path under unperturbed conditions is 0.005. After the Fuego eruption, the optical thickness rose to about 0.03. For such a layer a model of Harshvardhan & Cess (1976) predicts a cooling of the surface of about 0.8 K. The evidence that changes of surface temperature occur after volcanic eruptions has been reviewed by a number of authors (see, for example, Lamb 1970). Can we in addition expect changes in stratospheric aerosol due to man's activities? Baldwin *et al.* (1976) considered the possibility of a significant increase in stratospheric particles from high-flying aircraft and concluded that even if very large fleets of aircraft flew at high altitude, the optical thickness of the aerosols that they might produce would be several orders of magnitude less than for those from the Fuego volcano just discussed.

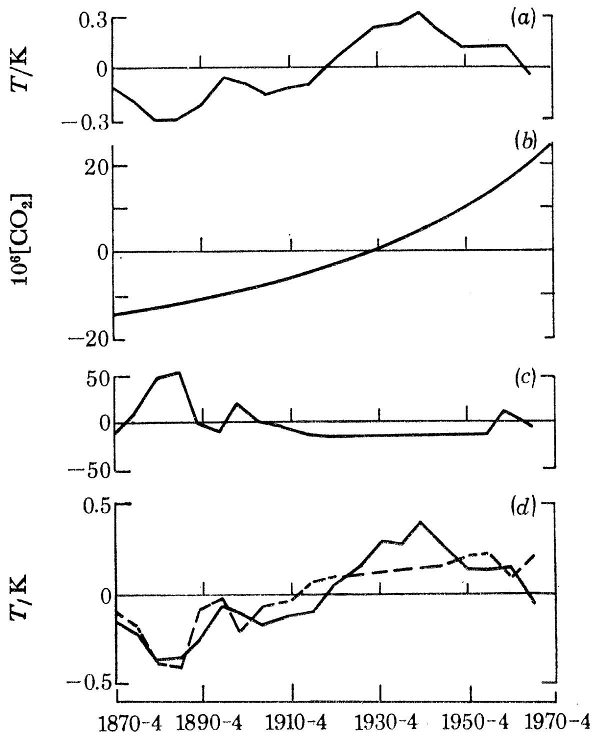

FIGURE 6. Five-year means over the Northern Hemisphere of (*a*) temperature anomaly; (*b*) CO_2 content (difference from 305 parts/10^6); (*c*) dust veil index (formed from annual values provided by Lamb (1970)); (*d*) actual temperature anomaly as in (*a*) (full line) compared with values predicted from multiple regression equation including CO_2 content and dust veil index only (broken line). (After Miles & Gildersleeves 1977.)

5. Evidence from atmospheric temperature measurements

A recent study by Miles & Gildersleeves (1977) has looked into the changes in average temperature of the Northern Hemisphere over the last hundred years and investigated to what extent these changes can be correlated with changes in atmospheric carbon dioxide and volcanic dust. Figure 6, taken from their paper, shows the basic data they employed. Their analysis shows that 65 % of the variance of hemispheric temperature can be explained by a multiple regression equation including only CO_2 concentration and volcanic dust veil index (figure 6). On the basis of this analysis, 0.4 K of the warming of *ca.* 0.6 K up to 1940 resulted from CO_2 (0.1 K) and from clearance of the dust veil (0.3 K). Miles & Gildersleeves's analysis further attempted, by including the ice index (figure 6) in their regression equations, to estimate the magnitude of the feedback arising from the presence of arctic ice. They conclude that of the 0.4 K warming mentioned above, approximately one-third is a result of ice feedback.

If the value of 0.1 K for warming from CO_2 before 1940 is extrapolated to what would happen if CO_2 increased by a factor of 2, a warming of about 1.5 K results, a very similar value to that found from the models reported in § 2. It must, however, be emphasized very strongly that the existence of correlations does not in any sense prove causal connections. However, as Miles & Gildersleeves point out, they do put some limit to speculation.

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