The Effect of Changing CO_2 Concentration on Radiative Heating Rates

R. E. NEWELL AND T. G. DOPPLICK

Dept. of Meteorology, Massachusetts Institute of Technology, Cambridge

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Carbon dioxide is the largest global pollutant by mass and atmospheric concentrations are increasing at about 0.7 parts per million by volume (ppmv) per year. The influence of this change on the atmospheric temperature structure is unknown; it can be investigated by three progressively more complicated techniques. In the first, one seeks the radiative equilibrium temperature profile (variation with height) for different levels of CO_2 concentration, implying that there is no net radiative flux divergence at any point in the atmosphere. The approach has been used by a number of workers, Möller (1963) and Manabe and Wetherald (1967) being the most recent. The latter authors also incorporated a convective adjustment so that one aspect of atmospheric motion was included. In fact, there are no extensive regions in the atmosphere where the local change of temperature by radiative processes is zero (e.g., see Newell *et al.*, 1970). In the second approach, illustrated here, one computes the radiative heating rate as the local imbalance of radiative fluxes, for each altitude and for different CO_2 mixing ratios, keeping other factors constant. The third approach would be to include the other factors governing local temperature such as latent heat liberation, cloudiness, air motion, change in water vapor content, change in CO_2 content with change in oceanic temperature, and so on. Only the ESSA Geophysical Fluid Dynamics Laboratory group (e.g., Manabe, 1969; Bryan, 1969) could consider this possibility.

Radiative heating rates have been computed using Rodgers' (1967) work; the details are presented elsewhere (Dopplick, 1970). The present note is a simple application of the work. The local rate of temperature change produced by infrared radiative divergence due to CO_2, H_2O and O_3 appears in Table 1. It can be seen that at lower levels the net cooling rate is slightly diminished while at upper levels it is significantly increased by a change in CO_2 from 320 to 400 ppm. The physical reasons for the two changes differ. Consider a layer in the troposphere centered at 800 mb. The pressure thickness which gives the layer approximately unit

TABLE 1. Cooling rates (°C day^{-1}) by net thermal radiation for different CO_2 levels.

Layer (mb)	January (40N)			July (40N)		
	320 ppmv	400 ppmv	Difference	320 ppmv	400 ppmv	Difference
5–10	−2.696	−2.901	−0.205	−3.344	−3.597	−0.253
10–15	−1.998	−2.214	−0.216	−2.470	−2.748	−0.278
15–20	−1.860	−1.989	−0.129	−2.035	−2.194	−0.159
20–30	−1.309	−1.379	−0.070	−1.220	−1.299	−0.079
30–50	−0.692	−0.725	−0.033	−0.502	−0.537	−0.035
50–70	−0.386	−0.402	−0.016	−0.157	−0.172	−0.015
70–100	−0.301	−0.310	−0.009	−0.008	−0.012	−0.004
100–150	−0.268	−0.272	−0.004	−0.118	−0.121	−0.003
150–200	−0.470	−0.471	−0.001	−0.575	−0.575	0.000
200–300	−1.216	−1.216	0.000	−2.113	−2.113	0.000
300–500	−1.438	−1.436	0.002	−1.991	−1.985	0.006
500–700	−1.357	−1.349	0.003	−1.694	−1.679	0.015
700–850	−1.258	−1.246	0.012	−1.924	−1.906	0.018
850–1000	−1.269	−1.255	0.014	−2.038	−2.019	0.019

TABLE 2. Components of radiative heating (°C day^{-1}) at 40N for July with a CO_2 content of 320 ppmv.

Layer (mb)	Thermal radiation			Solar radiation		
	H_2O	CO_2	O_3	O_3	$(H_2O+CO_2+O_2)$*	Total
5–10	−0.37	−2.26	−0.71	2.97	0.37	0.00
850–1000	−1.79	−0.25	0.00	0.01	0.54	−1.50

* Near infrared.

optical depth for radiation absorbed by CO_2 can easily be obtained from the curves of absorption vs "pressure × path" in the literature. Using Brooks' (1958) curve for example and a factor of 1.66 for the diffuse character of the radiation gives unit optical depth for a slab as $\sim$150 mb if the CO_2 mixing ratio is 320 ppmv and about 120 mb for 400 ppmv. At 800 mb part of the flux from below originates from the surface and is attenuated en route, while part comes from the layer in between. The first part will decrease as the mixing ratio and therefore attenuation increases; the second part likewise decreases because it is governed by the effective temperature and, as it is the CO_2 close to the level that counts most, this effective temperature is slightly lower (provided temperature decreases with altitude as it does in the selected cases). The infrared flux arriving at 800 mb from above is governed again by the effective temperature which is a little higher for the larger mixing ratio as the important radiation originates from slightly lower altitudes and this flux value therefore increases. With less radiation coming up from below and more radiation coming down from above, the local cooling rate is diminished, but note that the effect is small, i.e., about a hundredth of a degree per day. In the stratosphere the pressure broadening effect dominates over the temperature increase with altitude, and the net effect of increasing CO_2 is to increase the cooling rate by several tenths of a degree per day.

The total column divergence of thermal radiation (net upward radiation at 5 mb minus that at 1000 mb) is 140,012 and 139,908 ergs cm^{-2} sec^{-1} for 320 and 400 ppmv, respectively, for January, while in July the corresponding figures are 196,009 and 195,487 ergs cm^{-2} sec^{-1}. Between 100 and 500 ergs cm^{-2} sec^{-1} additional radiation are therefore available to the atmosphere for the higher CO_2 concentration, corresponding to columnar heating rates of $1\text{–}5\times10^{-3}$C day^{-1}.

The greenhouse theory as usually discussed puts such a "heating" interpretation on the CO_2 changes even though the actual effect of a CO_2 increase is to diminish the cooling rate. It is well to stress that the conditions here are such that all other items are unchanged. The term greenhouse is of dubious applicability because the greenhouse glass leads to higher temperatures by reducing turbulent eddy heat losses, rather than by a radiative influence (Kondratyev, 1965).

To place the CO_2 contribution to temperature change in perspective it is compared with other radiative components at two levels in Table 2. Clear skies are assumed. Carbon dioxide is secondary to water vapor in the troposphere as noted by others (e.g., Rodgers and Walshaw, 1966) and dominant in the lower stratosphere under the conditions assumed here. When looking for a potential influence of global pollution on the tropospheric temperature it would therefore be wise to pay careful attention to the water cycle and its possible modification, particularly as it enters also through the effect of latent heat.

Note added in proof. Prof. J. London has drawn our attention to a paper by Gebhart (1967) which emphasizes the absorption of solar near infrared radiation by CO_2 and the tendency to compensate thermal radiation changes. Numerical comparisons will be made in a future paper.

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