On the Influence of Changes in the CO_2 Concentration in Air on the Radiation Balance of the Earth's Surface and on the Climate

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Abstract. The numerical value of a temperature change under the influence of a CO_2 change as calculated by Plass is valid only for a dry atmosphere. Overlapping of the absorption bands of CO_2 and H_2O in the range around 15 μ essentially diminishes the temperature changes. New calculations give $\Delta T = +1.5°$ when the CO_2 content increases from 300 to 600 ppm. Cloudiness diminishes the radiation effects but not the temperature changes because under cloudy skies larger temperature changes are needed in order to compensate for an equal change in the downward long-wave radiation. The increase in the water vapor content of the atmosphere with rising temperature causes a self-amplification effect which results in almost arbitrary temperature changes, e.g. for constant relative humidity $\Delta T = +10°$ in the above-mentioned case. It is shown, however, that the changed radiation conditions are not necessarily compensated for by a temperature change. The effect of an increase in CO_2 from 300 to 330 ppm can be compensated for completely by a change in the water vapor content of 3 per cent or by a change in the cloudiness of 1 per cent of its value without the occurrence of temperature changes at all. Thus the theory that climatic variations are effected by variations in the CO_2 content becomes very questionable.

In a series of publications, *Plass* [1956*a*, *b*, *c*, 1961*a*, *b*] has shown that variations in the CO_2 concentration in the air change the long-wave downward radiation of the atmosphere and, thereby, the heat lost by radiation from the earth's surface. Increasing the CO_2 content increases the atmospheric radiation or diminishes the radiation loss from the surface. The disturbed radiation budget will be compensated for, other things being equal, by an increased surface temperature. Plass therefore believes that a cause of climatic variations during geological and recent time has been found in the variations in the CO_2 content.

A variation in the insolation is justly neglected, for the absorption of the solar radiation by CO_2 is so small that its change can be disregarded. Variations in the radiation budget, however, will be followed by changes in the entire heat budget of the surface; heat consumption by evapotranspiration and transfer of sensible heat to the atmosphere will be changed, and water vapor content, vertical lapse rate of temperature, and cloudiness will be changed in the same way. Plass has tried to estimate qualitatively all these secondary effects. The starting point of all considerations, however, has to be the numerical value of the variations in the long-wave radiation.

It is useful in the following considerations to use the concept of long-wave, outgoing, net radiation E of the earth's surface (effective outgoing radiation) which is the negative value of the radiation budget in the long-wave spectral region or the difference $E = \sigma T_s^4 - A$, where T_s is the surface temperature and A is the downward terrestrial radiation; the absorptivity of the earth's surface is taken to be unity.

The increase in the long-wave outgoing radiation of the surface with a decrease in the CO_2 content to half its present value is, according to Plass, 12.5 mcal/cm² min and the decrease in the radiation with doubled CO_2 content is 11.9 mcal/cm² min. From these values, Plass derives temperature changes of $-3.8°$ and $+3.6°$, respectively. *Kaplan* [1960, 1961] has attacked these calculations and has pointed out that Plass did not take into account the influence of cloudiness on the radiation. With a half overcast sky and an average distribution of the clouds at different levels of the atmosphere, the long-wave net radiation of the surface is diminished by 38 per cent, according to Kaplan, and in the same way the influence of a CO_2 change on the radiation change is reduced. Kaplan's considerations appear to be justified, for the cloudiness present in the natural atmosphere must not be neglected. We shall show, however, that Kaplan is wrong in deducing that the resulting temperature change is diminished to 62 per cent.

Different numerical values are obtained by the two authors, perhaps because they used different absorption quantities. The results are not exactly comparable because Kaplan used two model atmospheres having surface temperatures of 40° and 0°C and Plass used T_s = 15°C. There are also small differences in their lapse rates. Cutting off the atmosphere at 100 mb will lead to wrong values of the long-wave emission to space. The influence of that measure on the net radiation from the ground is small, however (it is overestimated by Plass).

Both Plass and Kaplan neglect the fact that between 12 and 18 μ, in the wavelength range of CO_2 absorption, water vapor absorbs also, reducing further the radiation budget of the earth's surface. This influence has been studied by *Kondrat'ev and Niilisk* [1960]. They also investigated the influence of varied temperature stratifications and showed that it is small. The water vapor absorption, however, diminishes the net radiation from the surface in the range of the CO_2 band to 34 per cent of its value in an absolutely dry atmosphere and correspondingly diminishes the effect of CO_2 variations on the surface temperature. Kondrat'ev does not take into account the influence of cloudiness. All essential numerical values are given in Table 1.

To get a clear judgment, the radiation effects with and without water vapor and with and without cloudiness have been recalculated. These results are also shown in Table 1.

The basis of the calculations was a standard atmosphere with the following characteristics: temperature at the surface 15°C, lapse rate 6.5°/km, stratosphere isothermal at −55°C, temperature of the ground equal to that of the lowest air layer, CO_2 concentration of 300 ppm, and relative humidity 75 per cent or absolute humidity at the surface 9.7 g/m³ (Kondrat'ev used 10.0 g/m³). When the pressure effect on the absorption is assumed proportional to p/p_0 for both CO_2 and H_2O, the effective mass is 121.7 cm CO_2 at STP and the effective water vapor mass of the entire atmosphere is 1.73 cm liquid equivalent. In further calculations, the CO_2 concentration was varied to 330, 600, and 150 ppm, i.e. increased by 10 and 100 per cent and decreased to 50 per cent of its normal value.

In the spectral range from 12.0 to 18.0 μ (ν = 833 to 546 cm⁻¹) those transmission functions and generalized absorption coefficients are used which are given by *Elsasser and Culbertson* [1960] for both gases in Tables 3, 7, 8, and 10 of their monograph. For the continuous share of the water vapor absorption, the function $[1 - \exp(-1.66u)]$ was introduced as an approximation to $2\,H_3\,(u)$. The overlapping of CO_2 and H_2O absorption bands was taken into account in the usual way by multiplying the transmissivities of CO_2 τ_c and H_2O τ_w, i.e., $\tau = \tau_c\tau_w$.

To integrate the contributions to the down-

TABLE 1. Effective Outgoing Radiation from the Earth's Surface in the 12- to 18-μ Band and Change in the Effective Radiation with Change in the CO_2 Concentration, in mcal/cm² min

Values in parentheses refer to calculations with *Yamamoto and Sasamori*'s [1961] absorption values.

Author	Condition	CO_2 Content, ppm 150	300	330	Change of CO_2 Content 300–330	300–150	300–600
			cloudless				
Plass	15° without H_2O					+12.5	−11.9
Kaplan	40° without H_2O	79.8	68.3	66.8	−1.5	+11.5	
Kaplan	0° without H_2O	54.7	47.7	46.8	−0.9	+7.0	
Kondrat'ev	10° without H_2O	70.4	62.8	61.6	−1.2	+7.6	
Kondrat'ev	10° with H_2O	23.3	21.3	20.8	−0.5	+2.0	
Möller	15° without H_2O	61.5	54.9	54.0	−0.9	+6.6	−6.4
Möller	15° with H_2O	33.7	30.3	29.8	−0.45	+3.4	−3.3
					(−0.60)	(+4.6)	(−4.4)
			½ cloudiness				
Kaplan	40° without H_2O	49.2	42.3	41.4	−0.9	+6.9	
Kaplan	0° without H_2O	34.1	29.9	29.3	−0.6	+4.2	
Möller	15° without H_2O	39.4	35.2	34.7	−0.51	+4.2	
Möller	15° with H_2O	22.4	20.2	19.9	−0.32	+2.2	−2.2
					(−0.43)	(+3.0)	(−3.0)

ward radiation of the different layers, the atmosphere was subdivided into layers according to its temperature. The temperature range in the layer closest to the ground was only 0.1°. The boundary temperatures of the layers (in degrees), beginning at the ground, were 15, 14.9, 14, 13, 12, 11, 10, 5, 0, —10, —20, —30, —40, —50, and —55. The particularly narrow subdivision close to the reference level (earth's surface) was necessary because of the strong absorption of very thin layers at some wavelengths (1-km steps as used by Plass appear to be too thick close to the ground). The calculations were made separately for ten wavelength regions

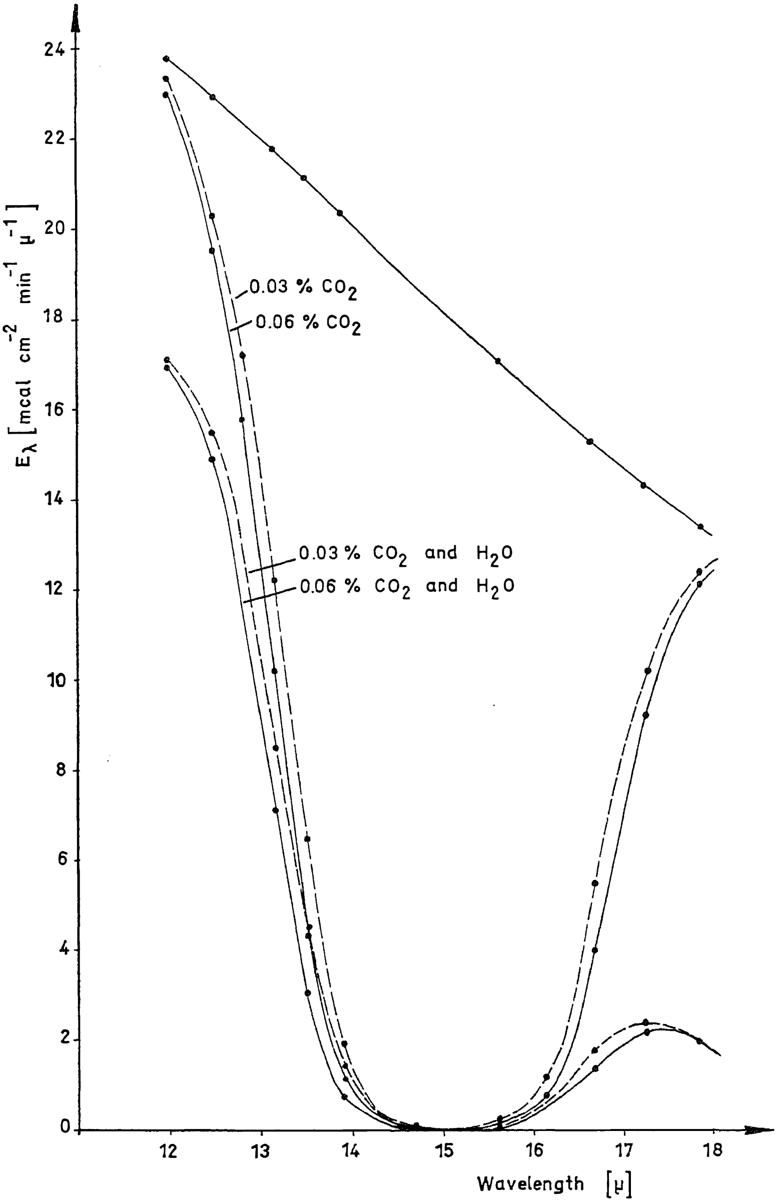

Fig. 1. Outgoing effective (net) radiation from the earth's surface, for CO_2 concentration of 0.03 per cent by volume (dashed) and 0.06 per cent by volume (full line), without (upper lines) and with (lower lines) simultaneous absorption by water vapor. Uppermost line, blackbody emission of the earth's surface at 15°C.

within the interval 12.0 to 18.0 μ and then integrated over the total range (Plass used six partial intervals and Kaplan used five).

The method of calculation is illustrated by Figures 1 and 2. Figure 1 shows the spectral distribution of the effective outgoing radiation when absorption is by CO_2 only. The changes evidently occur mainly in the wings of the 15-μ band. With overlapping of the H_2O absorption band the effective radiation is slightly diminished at the short-wave side of the band but is strongly decreased at the long-wave side. Thus essential changes occur in small spectral ranges only.

The differences between the outgoing radiation for CO_2 concentrations of 300 and 600 ppm are shown in Figure 2, with and without the action of H_2O. The radiation quantities were integrated over the wavelengths according to Figure 1 only for the standard CO_2 concentration with and without H_2O. For the other CO_2 concentrations only the difference curves were integrated according to Figure 2. The results are shown in Table 1, which also contains the most important results of the calculations of other authors.

The variation in the outgoing radiation from the earth's surface for a decrease in the CO_2 content to half of its normal amount, given in the first line of Table 1 (after Plass), is +12.5 mcal/cm² min for the water-free atmosphere having a surface temperature of 15°C. Kaplan's corresponding value is +11.5 units for a surface temperature of 40°C and +7.0 units for 0°C. Kondrat'ev obtains +7.6 units for 10°C, whereas the present result is +6.6 units for 15°C. The greater part of these differences may be caused by differences in the absorption values; the smaller part may be due to different ways of integration over atmospheric layers and wavelengths.

If the H_2O absorption is taken into account, Kondrat'ev's and our figures are diminished to 2.0 (26 per cent) and 3.4 mcal/cm² min (52 per cent), respectively. The difference may be caused by the fact that Kondrat'ev did not introduce a spectral subdivision in calculating the overlap effects of CO_2 and H_2O.

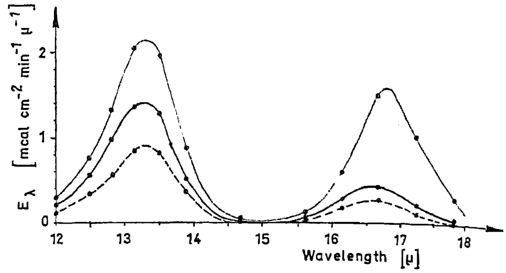

Fig. 2. Outgoing net radiation from the earth's surface, difference between the cases with 0.03 and 0.06 per cent by volume of CO_2. Upper thin line, clear sky, no water vapor; middle thick line, clear sky, with water vapor; lower dashed line, ½ cloudiness, with water vapor.

Next, the influence of cloudiness on the calculations is introduced, with and without H_2O absorption. To obtain comparable values it was decided to use the same cloudiness (½) and the same vertical distribution of clouds (Table 2) as Kaplan did, although better statistical data are now available for the average distribution of the upper and lower surfaces of clouds with height [*de Bary and Möller*, 1960].

When he took the cloudiness into account, Kaplan obtained a decrease to 60 per cent of his value with cloudless skies, whereas these calculations give a decrease to 64 per cent. Taking H_2O and cloudiness into account, we find that changes in the effective long-wave radiation of only +2.2 mcal/cm² min occur with half and of −2.2 units with twice the normal CO_2 content. This is only 18 per cent of the original values of Plass.

These small values may be caused partly by the use of Elsasser's absorption figures. These are in good agreement with the experimental data of *Howard et al.* [1956]. The absorptivities which are based on the theoretical calculations of *Yamamoto and Sasamori* [1961] are much smaller, and Plass's values are lower yet. Yamamoto's values were recently verified by the experiments of *Burch et al.* [1960], and they now appear to be the most reliable ones (Figure 3). To get a quick estimation of the influence of other absorptivities the effective spectral radia-

TABLE 2. Distribution of Cloud Ceilings (after Kaplan)

p, mb	900	800	700	600	500	400	300	200	cloudless
T, °C	9	2	−5	−12	−21	−32	−44	−55	
N	0.15	0.15	0.05	0.05	0.025	0.025	0.025	0.025	0.50

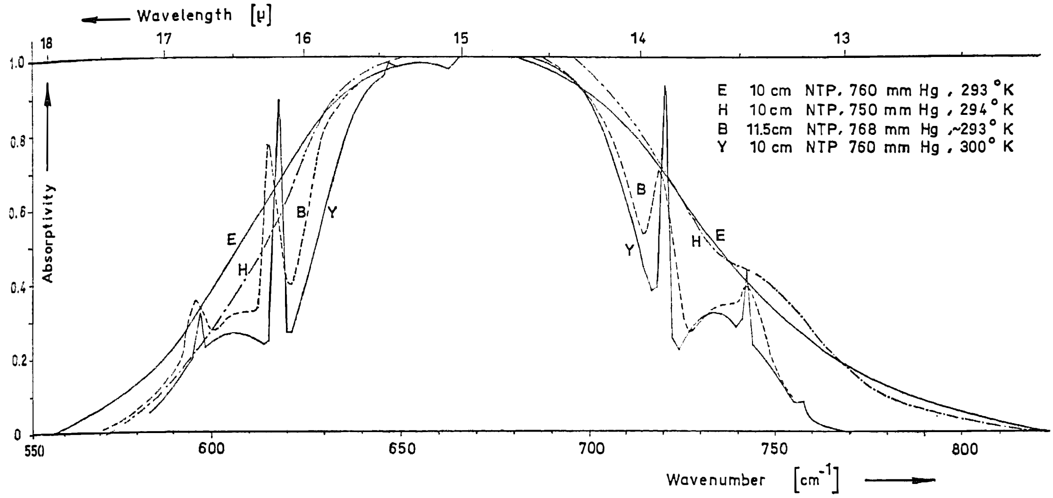

Fig. 3. Absorption of CO_2 within the 15-μ absorption band. E calculated with Elsasser's data, H measured by Howard et al., B measured by Burch et al., Y calculated by Yamamoto and Sasamori. Absorbing quantities and conditions as indicated.

tion from the surface for the case of an isothermal atmosphere was calculated. Instead of the change of +3.4 mcal/cm² min (after Elsasser) when the CO_2 content is halved (Table 1), we obtain for the isothermal atmosphere +3.06 units. When we use the absorption numbers of Yamamoto and Sasamori we obtain +4.11 units. The ratio between these two values is 1.34. Thus we may assume that all the figures given in columns 6 to 8 of Table 1 for these values are to be enlarged by ⅓ when the smaller absorptivities of Yamamoto are used. Because these absorptivities are more reliable, the factor 1.34 shall be applied in all further considerations. Also, with this correction the changes in the outgoing radiation in column 7 are increased to +4.6 and +3.0 units.

The most difficult, but meteorologically the most essential, question is which temperature changes are effected by such changes in the long-wave net radiation from the surface. Kondrat'ev simply uses the change in the black radiation, which amounts to 8 mcal/cm² min deg at a temperature of +15°C. It is not permissible, however, to assume that an increase in the downward atmospheric radiation caused by an increased CO_2 content can be compensated for by an increased black radiation of the same amount from the ground. With a warmer surface the air layer adjacent to the surface will also be heated so that a temperature difference between ground and air will not occur. This can be taken into account by considering the change with temperature in the net radiation at the surface,

$$\partial E/\partial T_s = \partial(\sigma T_s^4 - A)/\partial T_s$$

where the downward atmospheric radiation A has to be taken for the standard atmosphere of the surface temperature $T_s = 15°C$.

The correct condition for the change in the surface temperature is that the radiation budget of the earth's surface must remain unchanged. If S denotes the solar global radiation absorbed by the earth's surface and E denotes the outgoing long-wave net radiation, this condition is $S - E =$ constant. S will not be changed because the influence of the CO_2 absorption on the solar radiation S can be neglected. When E is decreased by an increased CO_2 content, it must be increased again by raising the temperature so that the radiation budget $(S - E)$ is kept in balance. The quantity $\partial E/\partial T_s$ for the given standard atmosphere ($T_s = 15°C$, $f = 75$ per cent) is found to be equal to 2.7 mcal/cm² min deg by evaluation from the radiation diagram of Möller. By calculating a greater number of cases in the same diagram *Möller* [1954] found an approximate interpolation formula,

$$E = (115.0 - 3.24\tau_s - 0.0185\tau_s^2 + 3.0T_s) \times 10^{-3} \qquad (1)$$

where T_s and τ_s are the temperature and dew point in °C. This formula gives the similar value +3.0 mcal/cm² min deg for the same differential quotient. Plass assumed that a change of +3.3 mcal/cm² min corresponds to a temperature change of 1.0°. Both of our values do not differ much from Plass's assumption. Kaplan used Plass's values.

Using the value $\partial E/\partial T_s = 3.0$ mcal/cm² min deg we obtain from the values in parentheses in Table 1 an increase (decrease) in temperature of 1.5° when the CO_2 content is doubled (halved). This is about 40 per cent of the effect determined by Plass.

Plass [1961*a*] has stressed that, for an increase in the ground temperature, the atmosphere, at least in its lowest layers, will also be heated and will then be able to contain a larger amount of water vapor. The atmospheric downward radiation will then be enlarged, and this will again effect a heating of the earth's surface. In this way there will exist a self-intensifying or feed-back effect in the heating process.

The process of accumulation or loss of CO_2 in the atmosphere takes place very slowly (decades or centuries). The assumption of 75 per cent relative humidity in the atmosphere, therefore, will still be valid after the CO_2 change, for it is a consequence of the evapotranspiration or of the general circulation and is independent of the CO_2 concentration. At any rate, constant relative humidity is meteorologically more reasonable than the assumption of a constant absolute humidity.

In this case the conversion factor from heat units to temperature units is given by the reciprocal value of

$$\frac{dE}{dT_s} = \frac{\partial E}{\partial T_s} + \frac{\partial E}{\partial W}\left(\frac{dW}{dT_s}\right)_{f=75\,\%} \qquad (2)$$

where W, the total liquid equivalent of water vapor, is dependent on the temperature. The effective radiation E decreases with increasing water vapor content, so the second term in (2) is negative. The numerical value of (2) can be derived from (1) by differentiation. For $T_s = +15°$ and $\tau_s = +10.60$°C, which corresponds to $f = 75$ per cent, we find

$$dE/dT_s = -0.50 \text{ mcal/cm}^2 \text{ min deg} \qquad (3)$$

The negative sign means that an increase in the outgoing net radiation from the earth's surface will be obtained by a temperature fall when the relative humidity remains constant. An increase of the CO_2 content and of the downward radiation of the atmosphere will in this case be compensated for by a decrease in the surface temperature instead of an increase, which should be expected.

It is worth while to verify this result. It can be obtained from a formula based on calculations from Möller's diagram or from the Ångström formula which is inferred from measurements. Following Ångström we obtain the relationship $E = \sigma T_s^4\,[0.210 + 0.174 \exp(-0.127\epsilon_s)]$, where ϵ_s is the vapor pressure at the surface in mm of Hg. By total differentiation, and using $T_s = 15$°C, $\epsilon_s = 9.59$ mm of Hg, $(d\epsilon/dT)_{f=75\%} = 0.62$ mm of Hg/deg, one obtains $dE/dT_s = -0.23$ mcal/cm² min deg, which is a negative value as well. Any graphical representation of the Ångström formula [e.g., *Geiger*, 1961] shows the decrease of E with T_s when the relative humidity is constant.

The feed-back effect which was postulated by Plass does not exist.

This controversial result is obtained because the change in the insolation or global radiation with the water vapor content of the atmosphere was neglected. The water vapor content increases when the relative humidity remains constant and the temperature increases; the global radiation S is then diminished because of the stronger absorption and it is therefore not necessary for the effective outgoing radiation to increase so strongly.

Returning to the condition of the balanced radiation budget,

$$S(W) - E(T_s, W, c) = \text{constant} \qquad (4)$$

where c is the total CO_2 content of the atmosphere, we find by total differentiation that

$$\frac{dS}{dW}\frac{dW}{dT_s}\,dT_s - \frac{\partial E}{\partial T_s}\,dT_s - \frac{\partial E}{\partial W}\frac{dW}{dT_s}\,dT_s - \frac{\partial E}{\partial c}\,dc = 0 \qquad (5)$$

The last term is the change in the effective radiation ΔE, which was computed earlier and is given in Table 1. We obtain

$$\Delta T_s = \Delta E \Big/ \left(\frac{dS}{dW} \frac{dW}{dT_s} - \frac{\partial E}{\partial W} \frac{dW}{dT_s} - \frac{\partial E}{\partial T_s} \right) \tag{6}$$

The total expression in parentheses should be negative when a positive ΔE (with diminished CO_2 content) is expected to be followed by a decrease of the temperature, $\Delta T_s < 0$. The second and third terms in parentheses are $+0.50$ mcal/cm^2 min deg according to (3). The global radiation is composed of direct solar radiation and diffuse sky radiation. Sky radiation is stronger in the visible and ultraviolet spectral ranges and is much smaller in the infrared where the water vapor absorption bands are located. Only in an overcast sky may the diffuse infrared radiation become comparable to the visible part. We may therefore equate, to a first approximation, the decrease in global radiation with water vapor content and the quantitative value of the increase in absorption a of the direct solar radiation at an average zenith angle $\langle \zeta \rangle$ of the sun. Then

$$\frac{dS}{dW} = -\frac{I_0}{2} \frac{da(W \sec \langle \zeta \rangle)}{dW} \cos \langle \zeta \rangle$$

where I_0 is the solar constant. The most reliable values of a are given by *Yamamoto* [1962]. Assuming the water vapor content of the atmosphere (without the p/p_0 reduction) to be 2.12 cm ppw and $\langle \zeta \rangle$ to be 60°, we obtain from curve 3 in Figure 1 of Yamamoto's paper

$$dS/dW = -8.7 \text{ mcal/cm}^2 \text{ min cm l.e.}$$

(The abbreviation l.e. stands for 'liquid equivalent' of water vapor, which is used instead of ppw or precipitable water.) The assumption of an average zenith angle $\langle \zeta \rangle$ throughout the day and year is a rather rough approximation. A more representative value of the insolation can be obtained by counting the hours during which the sun's elevation has given values. At 50° latitude, the sun's zenith angle remains between the given limits for the times shown (in fractions of a year):

Zenith angle of the sun	90°		80°		70°		60°		50°		40°		30°
Time		0.102		0.137		0.080		0.077		0.053		0.057	

With these numbers, a similar calculation for the annual average gives $dS/dW = -7.0$ mcal/cm^2 min cm l.e. But $(dW/dT_s)_{f=75\%} = 0.137$ cm l.e./deg, so $(dW/dT_s)_{f=75\%} = -0.965$ mcal/cm^2 min deg. With this value and with (3) the term in parentheses in (6) is

$$d(S - E)/dT_s = -0.46 \text{ mcal/cm}^2 \text{ min deg} \tag{7}$$

Reducing the quantities of ΔE of Table 1 to the absorption values of Yamamoto and Sasamori and applying the conversion factor (7), we find for the cloudless atmosphere: $\Delta T = -10.0°$ when c is decreased to 50 per cent of its normal value, $\Delta T = +9.60°$ when c is increased to 200 per cent of its normal value, and $\Delta T = +1.30°$ when c is increased to 110 per cent of its normal value. Taking into account the feed-back effect of the water vapor, we find that these temperature changes are about 2.5 times larger than the numerical values given by Plass and 6.6 times larger than the above-computed values.

It is necessary, however, to find the temperature changes with clouds present. In this case the conversion factor (7) cannot be applied since with cloudiness the global radiation S and the long-wave net radiation E are much smaller and their changes with water vapor W and with temperature T_s are also smaller than with cloudless skies. To calculate E we can again use the formulas given by *Möller* [1954]. They are

$$E^{(N)} = E^{(O)}[1 - \sum N_i(1 - k_i)]$$

$$k_i = 0.043\Delta T_i^{0.7} \cdot (1 + 0.15f/100)(1 - 0.0027T_s)$$

where $E^{(N)}$ and $E^{(O)}$ are the effective outgoing radiation with cloudy and cloudless skies, respectively. $E^{(O)}$ is as given by (1), N_i and ΔT_i are the partial cloudiness and the temperature difference between the earth's surface and the ceiling of the cloud layer according to Table 2. After differentiating and introduction of all numerical values, we get

$$dE^{(N)}/dT_s = -0.40 \text{ mcal/cm}^2 \text{ min deg}$$

To obtain the variation in the global radiation S with water vapor content (for cloudy sky) we can assume that below the cloudless half of the sky the global radiation is unchanged and below the cloudy part only 40 per cent of the radiation is present. This rough estimation gives

$$dS^{(N)}/dT_s = 0.7(dS/dT_s)$$
$$= -0.68 \text{ mcal/cm}^2 \text{ min deg}$$

and the quantity in parentheses in (6) becomes (for cloudy sky) -0.28 mcal/cm^2 min deg.

Again using the quantities ΔE in parentheses in Table 1, which are reduced to the absorption values of *Yamamoto and Sasamori* [1961], we find for the cloudy sky: $\Delta T_s = -10.7°$ when c is decreased to 50 per cent of its normal value, $\Delta T_s = +10.7°$ when c is increased to 200 per cent of its normal value, and $\Delta T_s = +1.5°$ when c is increased to 110 per cent of its normal value.

All the conversion factors and their single terms are very uncertain or are based on estimates only. Therefore, we may assume that the temperature changes for cloudy skies do not differ from those for cloudless skies. Taking into account the diminution of the radiation by clouds, we obtain almost the same temperature changes as with cloudless skies because the conversion factors from radiation to temperature show almost the same variation as the radiation itself.

Conclusions. Cloudiness diminishes the quantitative influence of a CO_2 variation on the change in the radiation budget. This smaller change, however, must be compensated for by a temperature change of the same amount as in the cloudless case. Therefore, the influence of cloudiness that was shown by Kaplan does not exist.

The changes in the long-wave radiation with increased or decreased CO_2 content as found by Plass are noticeably diminished when the absorption of water vapor in the same spectral range is taken into account. This has already been shown by Kondrat'ev and Niilisk.

In this case, we must distinguish between the assumptions that the water vapor content (in cm l.e.) remains unchanged in spite of the heating (cooling) of the atmosphere and that it increases (decreases). Constant absolute humidity means that the relative humidity f decreases from 75 to 70.34 per cent with a temperature increase of 1° or is lowered by 4.66 per cent per deg. According to the above-mentioned calculations, an increase of CO_2 from 300 to 600 ppm gives a temperature change $\Delta T_s = +1.5°$ for $\Delta f = -4.66$ per cent per deg, and a temperature change $\Delta T_s = +9.6°$ for $\Delta f = 0$. The feed-back effect as shown by these values was found only when the change in solar radiation with change of water vapor content was also taken into account. The influence of the water vapor variations is very strong. It is not possible, however, to demonstrate definitely which change of water vapor content will occur when the temperature changes. For two other assumptions we can similarly derive a temperature change $\Delta T_s = +2.6°$ for $\Delta f = -2.33$ per cent per deg, and a temperature change $\Delta T_s = -5.6°$ for $\Delta f = +2.33$ per cent per deg. We recognize that for $\Delta f = +0.8$ per cent per deg the temperature change becomes infinite. Very small variations effect a reversal of sign or huge amplifications.

We know that the atmosphere does not react in this way. Similar conditions are given with the release of condensation heat in the large precipitation areas of atmospheric lows. This never effects a complete turnover or a remodeling of the weather situation. Instead, a quite steady development is observed which can rather realistically be imitated by the hydrodynamic equations without energy supply. I should like to say that nature does not like excesses. If there are too many degrees of freedom for a given variation, other smaller variations will occur. There are many possibilities for such an occurrence in the case studied in this paper. Small variations in the relative humidity or in the cloudiness may effect such changes. The following survey allows a judgment of these influences.

In an atmosphere with $T_s = 15°$, $f = 75$ per cent, or $W = 2.1$ cm l.e., CO_2 content $= 300$ ppm, cloudiness $= 0.5$, the long-wave outgoing net radiation from the earth's surface is $E = 84$ mcal/cm^2 min. The following effects are found:

(*a*) An increase in CO_2 content from 300 to 330 ppm causes $\Delta E = -0.4$ mcal/cm^2 min or -0.5 per cent of E.

(*b*) An increase in temperature from 15° to 16° causes $\Delta E = +1.8$ mcal/cm^2 min or $+2.2$ per cent of E.

(*c*) An increase in water vapor content from

2.12 to 2.33 cm l.e. (+10 per cent) or in the relative humidity from 75 to 82.5 per cent causes $\Delta E = -3.5$ mcal/cm^2 min or -4.1 per cent of E.

(*d*) An increase in cloudiness from 0.5 to 0.55 (+10 per cent) causes $\Delta E = -4.0$ mcal/cm^2 min or -4.7 per cent of E.

(*e*) An increase in water vapor content from 2.12 to 2.33 cm l.e. (+10 per cent) or in the relative humidity from 75 to 82.5 per cent causes $\Delta S = -2.2$ mcal/cm^2 min.

(*f*) An increase in cloudiness from 0.5 to 0.55 (+10 per cent) causes a change in the global radiation (according to a table given by *Sauberer and Härtel* [1959]) of approximately $\Delta S = -8.2$ mcal/cm^2 min.

It is not difficult to infer from these numbers that the variation in the radiation budget from a changed CO_2 concentration can be compensated for completely without any variation in the surface temperature when the cloudiness is increased by the amount +0.006 or the water vapor content is decreased by -0.07 cm l.e. In these values the changes in global radiation are taken into account, as well as the changes in the long-wave radiation as in (6). These are variations in the cloudiness by 1 per cent of its value or in the water vapor content by 3 per cent of its value. No meteorologist or climatologist would dare to determine the mean cloudiness or the mean water vapor content of the atmosphere with such an accuracy; much less can a change of this order of magnitude be proved or its existence be denied. Because of these values the entire theory of climatic changes by CO_2 variations is becoming questionable.

Finally, it should be emphasized that (4) is incomplete. At the earth's surface there is no equilibrium of the radiation processes but a heat balance in which the insolation S is compensated for by the transfer of sensible (L) and latent (V) heat from the surface to the air, and by the long-wave outgoing net radiation. Instead of (4) we get

$$S - E - L - V = 0 \qquad (8)$$

Variations in *one* term of this equation will effect variations in *all* the other terms generally, so that we may expect that the temperature changes as calculated above will decrease further when the complete heat budget is considered. An attempt will be made to study these connections at a later date.

The reasons that the CO_2 variations have so often been assumed to be causes of climatic variations may be:

(1) The CO_2 content of the atmosphere is so remarkably uniform over space and time that it is possible to observe long-range variations in its mean value. This is impossible for almost any other factor which can influence the radiation processes. Cloudiness, water vapor, and temperature show strong variations with day, season, latitude, and between oceans and continents. Observations are so scarce over about 60 per cent of the earth's surface that a secular variation in these factors cannot be recognized. CO_2 content is the only factor whose secular variation we know.

(2) The influence of CO_2 variations on the long-wave radiation seems to be evident because its physical mechanism is relatively clearly understood. It is, however, much more difficult to interpret its meteorological meaning and effects.

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