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Influence of various physical factors upon the radiative equilibrium of the atmosphere

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ABSTRACT. The effects of given variations in water vapour, carbon dioxide, and ozone upon the radiative equilibrium of the atmosphere have been investigated. The equilibrium temperature has been computed as an asymptotic steady state by marching process.

The study has shown that water vapour can alone account for 96·7 per cent of the temperature distribution of the troposphere, whereas ozone together with carbon dioxide can practically account for the temperature distribution of the stratosphere. Ozone is the only gas responsible for maintaining warm stratosphere. The surface albedo and hence the ground temperature plays a very important role in fixing the temperature distribution of the vertical column.

1. Introduction

Under the influence of radiative processes alone, the vertical distribution of temperature in the atmosphere tends to adjust itself in such a way that the heating caused by solar radiation and the cooling due to terrestrial radiation balance each other at every level. Absorption of solar radiation is a function of the amount of absorbing material, the solar altitude, and the albedo of the earth's surface and of clouds. The terrestrial radiation is determined by considering the radiative exchange processes between the various levels in the atmosphere and it is essentially a function of the distribution of the absorbing material in the vertical. In an earlier work (Godbole *et al.* 1970), hereafter referred to as paper A, the authors computed the radiative equilibrium temperature (RET) of the atmosphere using a model which incorporated the effects of the absorption of solar and terrestrial radiation by water vapour, carbon dioxide, and ozone, as well as the effects of convection. In the present work, the interaction between the heating and cooling components due to given changes in the amount of water vapour, carbon dioxide, and ozone and in the values of surface albedo has been investigated. Such a study would help understand the relative importance of each of these factors at different heights under different conditions and the sensitivity of the equilibrium temperature towards changes in each individual factors. Manabe and Wetherald (1967) have reported similar work but for given conditions which are widely different from those considered in the present study.

2. Method of computation

The method of approach to the problem consists of computing the RET for a given set of mean atmospheric conditions and recomputing it for arbitrary changes introduced in the mean atmospheric conditions. Changes considered are introduced only in one parameter at a time; other parameters remain unchanged from the mean values. The mean atmospheric conditions considered are those for the month of July at the location 22·5°N and 80°E which corresponds to one of the eighteen grid points at which RETs were computed in paper A. The heights and pressures of the sigma-levels used in the present study are shown in Tabel 1.

Paper A describes in detail the method of computation with convective adjustment of temperature. The same method is being adopted in the present study. The RET is computed by marching process with standard atmospheric temperature distribution (U. S. Standard Atmosphere, 1962) as initial condition. The iterations are continued in time steps of 6 hours until the difference between the daily mean temperatures on two consecutive days becomes less than 0·01 degree. Equilibrium is normally found to have reached after 800 time steps which corresponds to 200 days, and only in a few cases, the iterations had to be extended to 300 and even 400 days.

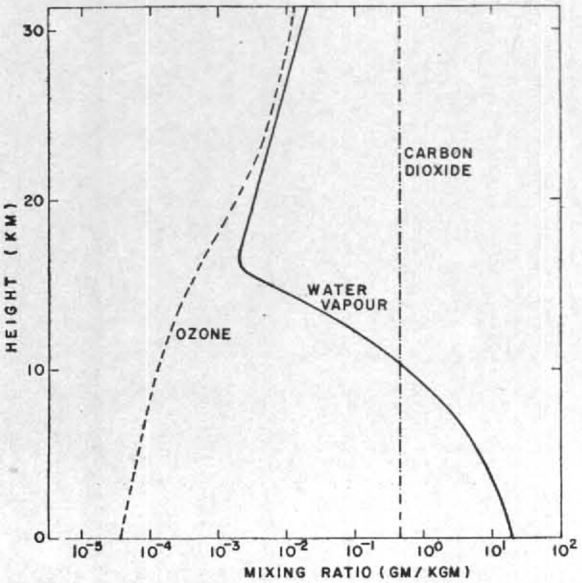

Fig. 1. Vertical distribution of the mixing ratio (gm/kgm) of water vapour, carbon dioxide and ozone for 22·5° N and 80°E. Mean for July

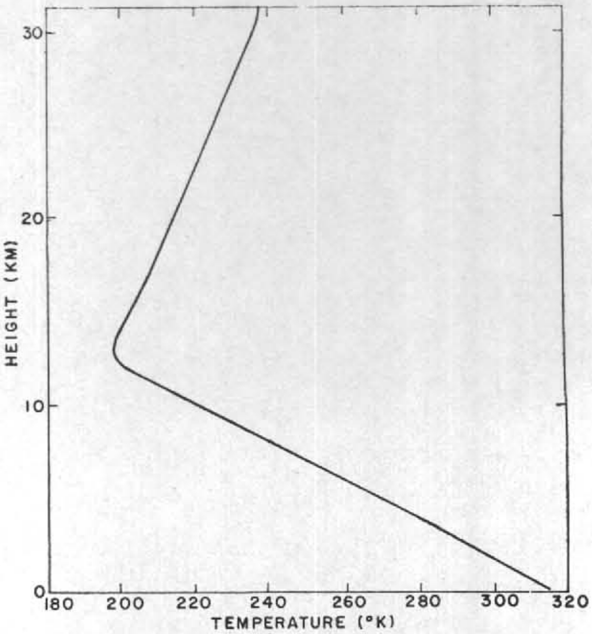

Fig. 2. Radiative equilibrium temperature with convective adjustment

3. Basic Data

The distributions of water vapour, carbon dioxide, and ozone used in the present study are shown in Fig. 1. The mixing ratio of water vapour below 500 mb has been obtained on the basis of the observed data for July 1964-65. Above 500 mb, the mixing ratio as shown in the figure has been extrapolated until a value corresponding to frost point of 190°K is reached. Thereafter, the mixing ratio has been assumed to follow constant frost point of 190°K (Manabe and Möller 1961). For convenience of computation the mixing ratio at the top of the atmosphere is assumed to be equal to one σ-level below it. At the earth's surface, the mixing ratio of water vapour is determined by using the relation $r_* = \beta r_s(T_*)$, where r_* is the mixing ratio at the earth's surface, β is a constant arbitrarily fixed and $r_s(T_*)$ is the saturation mixing ratio at the surface temperature T_*. The value of β considered in the present study is 0·6.

The mixing ratio of carbon dioxide has been assumed to be constant at 0·456 (gm/kgm) at all the levels. The ozone mixing ratio has been determined on the basis of the available observed data for July 1964-65. The values of cloud amount, surface albedo, absorptivity and emissivity, solar constant and solar altitude as considered in paper A are used in the present study.

TABLE 1

Heights of the sigma-levels and corresponding pressures

RETs are computed by the even levels only. Mixing ratios are specified at all levels

σ – level (k)	Value of σ	Height H (km)	Pressure P (mb)
½	·000	∞	0·00
1	·010	31·41	9·69
1½	·038	22·53	37·18
2	·082	17·61	80·11
2½	·140	14·25	136·10
3	·209	11·72	202·78
3½	·286	9·69	277·75
4	·369	7·96	358·65
4½	·456	6·46	443·12
5	·544	5·16	528·77
5½	·631	4·04	613·23
6	·714	3·08	694·16
6½	·791	2·26	769·14
7	·860	1·60	835·61
7½	·918	1·06	891·78
8	·962	·67	934·71
8½	·990	·44	962·22
9 (surface)	1·000	·35	971·919

$$\sigma_k = Q_k^2(3 - 2Q_k) = p_k / p_*$$

where,

$$Q_k = \frac{2k - 1}{17}, \quad k = \tfrac{1}{2},\ 9,\ \tfrac{1}{2}$$

and p_* is the surface pressure.

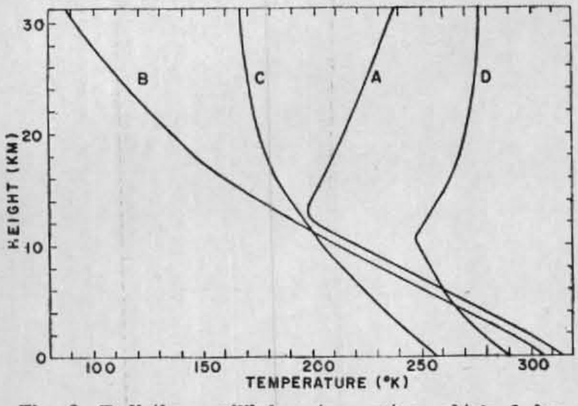

Fig. 3. Radiative equilibrium temperature obtained for (A) normal atmosphere (B) Water vapour atmosphere (C) Carbon dioxide atmosphere and (D) Ozone atmosphere

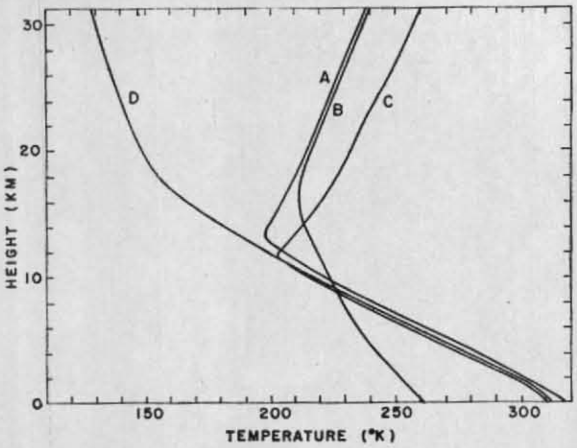

Fig. 4. Radiative equilibrium temperature, obtained for (A) Normal atmosphere (B) Water vapour absent (C) Carbon dioxide absent and (C)) Ozone absent

4. Results

1. *RET under normal conditions*

Fig. 2 shows the computed RET obtained with the observed mean distributions of water vapour, carbon dioxide, and ozone referred to above. The equilibrium condition was reached after 800 time steps or 200 days. The temperature distribution shows two regimes of lapse rate (positive and negative) typical of troposphere and stratosphere. Since an absorbing gas which decreases (increases) with height gives rise to cooling (warming) of the atmosphere, the positive lapse rate seen in the troposphere is mainly due to the water vapour. The negative lapse rate in the stratosphere is essentially due to the absorption of solar radiation by ozone.

2. *Effect of change in gas distribution on RET*

The individual contributions of water vapour, carbon dioxide, and ozone have been studied in three different ways. In the first instance, only one gas at a time is considered to be present in the atmosphere; subsequently, only one gas at a time is considered to be absent. Later, the effect of changes in the distribution of a single gas is studied, the other two gases having their normal mean distribution as shown in Fig 1.

Presence of one gas only — Fig. 3 shows the RETs obtained by condsidering only the presence of one gas at a time. For comparison, the RET obtained with normal distribution of gases (curve A) is also shown in the figure. It is seen that neither the water vapour atmosphere (curve B) nor the carbon dioxide atmosphere (curve C) shows either isothermalcy or inversion in the stratosphere. Instead, the temperature monotonically decreases with height in both the cases (curves B & C). Manabe and Strickler (1964), in a somewhat similar study, have arrived at the same results. However, the ozone atmosphere (curve D) shows the existence of tropopause but its height is lower than that of the normal atmosphere. On the whole, a comparison of RETs in Fig. 3 brings out the importance of ozone in maintaining warm stratosphere.

It is also seen from Fig. 3, that curve (B) runs very close and parallel to curve (A) frcm the surface upto about 12 km suggesting that water vapour plays the most dominant role in determining the radiative equilibrium of the troposphere. The water vapour atmosphere as well as the carbon dioxide atmosphere are seen to be colder than the normal atmosphere at all the heights. In addition, the carbon dioxide atmosphere is found to be colder than the water vapour atmosphere in the troposphere but warmer in the stratosphere. In the case of the ozone atmosphere, the deviation of RET is positive in the upper troposphere and stratosphere where the ozone is present in significant amounts.

Table 2 which gives the values of percentage deviation of RET due to an individual gas from that due to normal atmosphere shows quantitatively as to what extent the presence of one gas alone at a time accounts for the normal temperature distribution. The percentage deviation is uniformly low in the troposphere in the case of the water vapour atmosphere. The mean value of the percentage deviation noticed for the troposphere which is 3·25 suggests that water vapour atmosphere alone would account for 96·75 per cent of the temperature distribution of the entire troposphere.

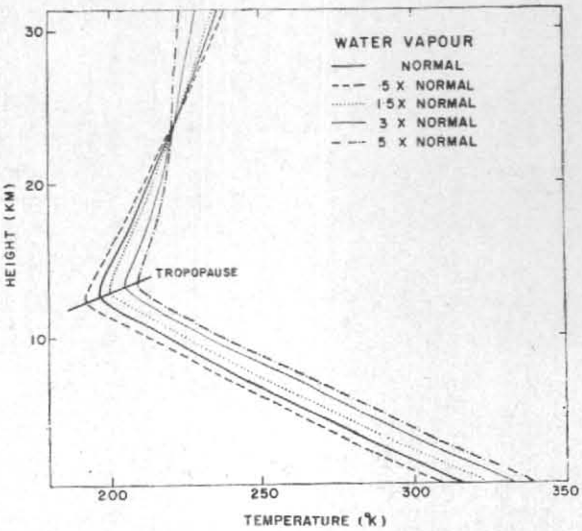

Fig. 5. Radiative equilibrium temperature for given changes in the mixing ratio of water vapour

TABLE 2

Percentage deviation of RET due to individual gas

The percentage deviation is expressed as —

$$\left(\frac{\text{RET due to individual gas — normal RET}}{\text{Normal RET}}\right) \times 100$$

RET is in °K

σ - level k	Height H (km)	Percentage deviation		
		Water vapour alone	Carbon dioxide alone	Ozone alone
1	31·41	—62·10	—29·45	+16·75
2	17·61	—27·60	—13·64	+28·10
3	11·72	—3·24	—2·16	+23·12
4	7·96	—3·26	—10·24	+6·51
5	5·16	—3·25	—15·03	—1·91
6	3·08	—3·29	—17·54	—5·84
7	1·60	—3·22	—18·67	—8·20
8	0·67	—3·24	—18·69	—8·20

TABLE 3

Percentage deviation of RET due to absence of one gas

The percentage deviation is expressed as —

$$\left(\frac{\text{RET due to absence of one gas — normal RET}}{\text{Normal RET}}\right) \times 100$$

RET is in °K

σ - level k	Height H (km)	Percentage deviation		
		Water vapour absent	Carbon dioxide absent	Ozone absent
1	31·41	+0·63	+9·24	—45·90
2	17·61	+1·63	+7·78	—25·02
3	11·72	+7·58	—1·52	—0·98
4	7·96	—4·43	—1·55	—1·00
5	5·16	—11·30	—1·51	—0·97
6	3·08	—14·78	—1·49	—1·00
7	1·60	—16·67	—1·51	—0·98
8	0·67	—17·32	—1·87	—0·99

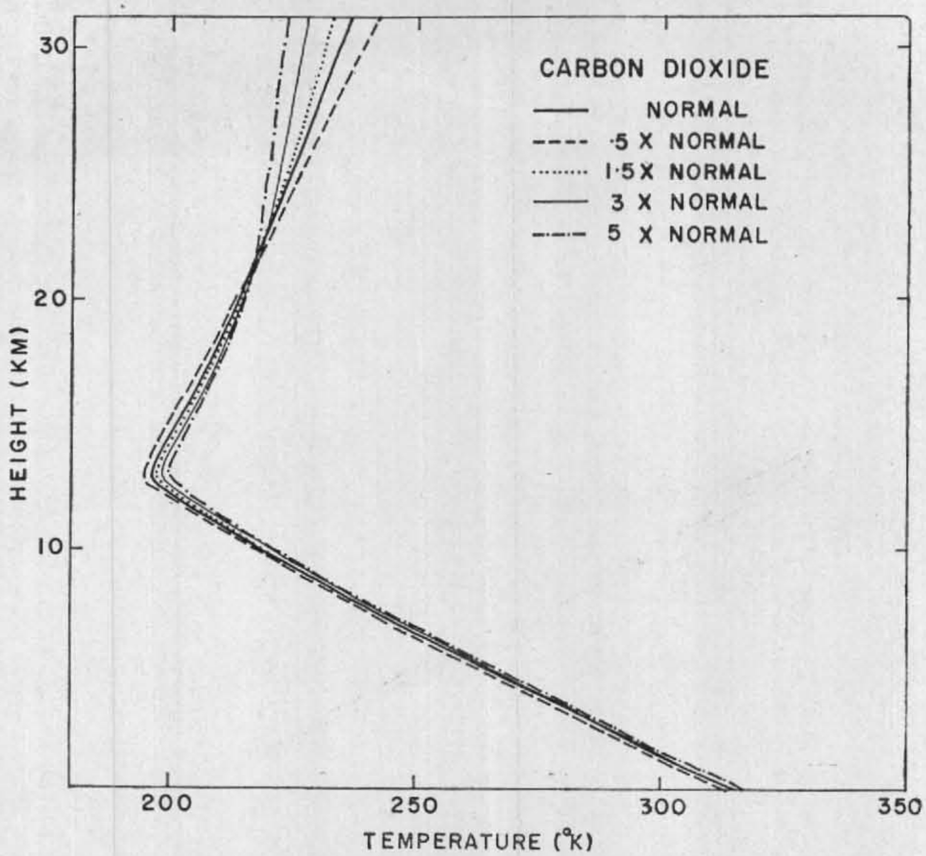

Fig. 6. Radiative equilibrium temperature for given changes in the mixing ratio of carbon dioxide

Absence of one gas — The RET due to the absence of one gas only at a time is shown in Fig. 4. For comparison, the normal RET (curve A) is also shown in the figure. Curves (C) and (D) which are obtained with water vapour as one of the gases present, run very close to each other and also to curve (A) all through the tropospheric region indicating once again the importance of water vapour in the lower troposphere. On the other hand, in the stratosphere, curves (B) and (C) which are obtained with ozone as one of the gases present run nearly parallel to each other. Also, these curves which are closer to curve (A) than curve (D) signify the importance of ozone in the stratosphere.

The values of percentage deviation of RET due to the absence of one gas from that due to normal atmosphere are shown in Table 3. The importance of water vapour in the troposphere is once again clearly brought out by the low values of the percentage deviation noticed in the two cases in which water vapour is present. In the stratosphere, ozone together with carbon dioxide could account for practically the entire temperature distribution, for the percentage deviations of RET noticed at the two levels considered in the stratosphere are only 1·63% and 0·63%.

Variation in one gas only — The mixing ratio of water vapour alone is considered to have changed at each level simultaneously in turn by 50%, 150%, 300% and 500% of its value in the normal atmosphere. The RETs arising from the changes made are shown in Fig. 5. It is found that an increase in the amount of water vapour increases the RET in the troposphere and lower stratosphere but decreases it in the upper stratosphere. It is also seen that an increase in water vapour content always tends to raise the height of the tropopause. This is on account of the increased cooling effect, due to the increase considered in the water vapour, extending to higher levels, before being compensated by the heating due to ozone. The tropopause has shifted upwards by 1·8 km when the mixing ratio of water vapour is increased by 5 times.

The magnitude of the deviation of RET obtained at each level as a result of the changes considered in the water vapour concentration is given in Table 4. A five-fold increase in the concentration has raised the temperature by 23·4°C at the sigma-level 5 which is 5·16 km.

The RETs obtained due to similar changes made in the amount of carbon dioxide are sh ow

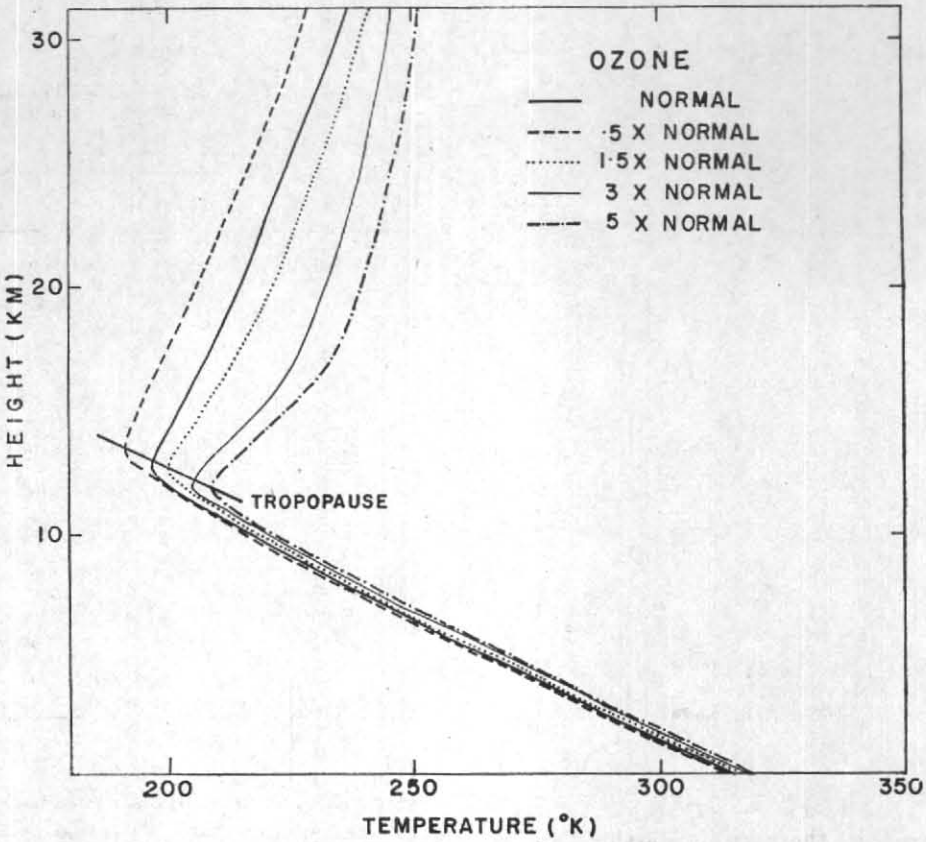

Fig. 7. Radiative equilibrium temperature for given changes in the mixing ratio of ozone

TABLE 4

Temperature deviation of RET due to changes considered in the water vapour mixing ratio from the normal RET

The temperature deviation is expressed as —

(RET due to changes in water vapour amount—Normal RET)

RET is in °K

σ – level k	Height H (km)	Temperature deviation for four different values of water vapour mixing ratio (%)			
		50	150	300	500
1	31·41	+2·7	—1·7	—7·8	—12·5
2	17·61	—2·4	+0·4	+5·5	+7·2
3	11·72	—5·6	+4·2	+12·0	+17·6
4	7·96	—6·6	+4·9	+14·1	+20·8
5	5·16	—7·3	+5·5	+15·8	+23·4
6	3·08	—8·6	+5·9	+15·8	+23·2
7	1·60	—9·1	+6·3	+16·6	+21·5
8	0·67	—10·2	+6·5	+16·9	+22·6

TABLE 5

Temperature deviation of RET due to changes considered in the carbon dioxide mixing ratio from the normal RET

The temperature deviation is expressed as —

(RET due to changes in carbon dioxide amount–Normal RET)

RET is in °K

σ – level k	Height H (km)	Temperature deviation for four different values of carbon dioxide mixing ratio (%)			
		50	150	300	500
1	31·41	+5·7	—3·2	—8·6	—12·1
2	17·61	—0·6	+0·7	+2·3	+3·7
3	11·72	—0·9	+0·5	+1·6	+2·4
4	7·96	—1·1	+0·6	+1·9	+2·8
5	5·16	—1·2	+0·7	+2·2	+3·2
6	3·08	—1·3	+0·7	+2·3	+3·4
7	1·60	—1·4	+0·8	+2·5	+3·7
8	0·67	—1·4	+0·8	+2·5	+3·8

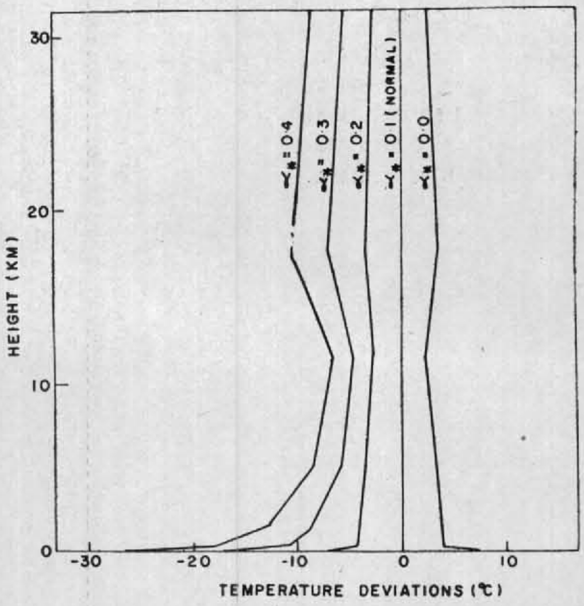

Fig. 8. Temperature deviations of RET from the normal RET for different values of surface albedo=0·1 for the normal atmosphere

TABLE 6

Temperature deviation of RET due to changes considered in the ozone mixing ratio from the normal RET

The temperature deviation is expressed as —
(RET due to changes in ozone amount — normal RET)
RET is in °K

σ - level k	Height H (km)	Temperature deviation for four different values of ozone mixing ratio (%)			
		50	150	300	500
1	31·41	—9·3	+4·1	+8·5	+15·2
2	17·61	—8·5	+6·7	+18·9	+26·0
3	11·72	—0·8	+0·6	+2·4	+4·3
4	7·96	—0·9	+0·7	+2·8	+5·0
5	5·16	—1·0	+0·9	+3·2	+5·7
6	3·08	—1·1	+0·9	+1·9	+2·7
7	1·60	—1·1	+1·0	+2·1	+2·7
8	0·67	—1·2	+1·0	+2·2	+2·7

in Fig 6. It is noticed that even the large variations considered in the carbon dioxide amount do not significantly alter the temperature distribution in the troposphere and lower stratosphere. Comparison with Fig. 5 points out that the effect due to the changes in carbon dioxide is in the same direction as that due to the changes in water vapour both in the troposphere and stratosphere, *i.e.*, an increase in its amount tends to increase the temperature in the troposphere and lower stratosphere but decreases the temperature in the upper stratosphere.

Table 5 gives the temperature deviations due to changes in the mixing ratio of carbon dioxide. As already stated, even a five-fold increase in the carbon dioxide amount hardly causes an increase in temperature by 4°C at the surface. Investigations by Manabe and Wetherald (1967) have pointed out that the surface temperature increases by about 2·3°C by doubling the carbon dioxide amount with realistic distribution of relative humidity. In the upper stratosphere, the temperature deviation is significantly large; being, 12·1°C at 31·4 km. The results lead to the inference that any conceivable long term variations in the concentration of carbon dioxide, due to the increased human activity, will not materially contribute towards changing the radiative equilibrium of the troposphere.

The RETs due to the changes made in the ozone mixing ratio are shown in Fig. 7. Unlike water vapour (Fig. 5) and carbon dioxide (Fig. 6) an increase (decrease) in ozone amount increases (decreases) the equilibrium temperature at all the levels in the atmosphere although the increase (decrease) noticed is very small in the troposphere as compared to that in the stratosphere. The height of the tropopause tends to decrease with increase in ozone amount which is opposite to what is noticed in the case of variations in the water vapour amount. The decrease noticed in the height of the tropopause is 1·5 km for a five-fold increase of ozone amount.

The temperature deviations obtained due to the changes made in the mixing ratio of ozone are given in Table 6. A five-fold increase in the ozone amount causes an increase of only 5·7°C at 5·16 km but as much as 26° C at 17·61 km.

3. *The effect of surface albedo on RET*

The mean value of the surface albedo a_* considered in the present study is 0·1. An increase in this value would cause less absorption of solar radiation into the ground which would result in the decrease of temperature not only at the surface but at higher levels also due to the reduced black body emission from the ground. On the other hand, an increase in a_* would make more amount of solar radiation available for re-absorption into the free atmosphere and hence tend to warm the atmospheric column. A study of the net effect of these two opposing phenomena on the RET is of interest. The results shown in Fig. 8, point out that an increase in a_*, while decreasing the surface temperature also decreases the RET of the entire atmospheric column. A variation of 0·1 in the value of a_* in the range 0·0 to 0·4, brings about a change of 9°C at the surface and 3° C in the stratosphere in the same direction. The results lead to the inference that the surface temperature which is, in turn, determined by the surface albedo, plays a prominent role in fixing the temperature of the lower troposphere. The effect of changes in the surface albedo is most pronounced at the ground and decreases with increase of height.

5. Conclusions

1. Water vapour and carbon dioxide affect the radiative equilibrium of the atmosphere in such a way that a decrease in the amount of either gas decreases the tropospheric temperatures but increases the stratospheric temperatures. However, water vapour has more dominating influence upon the tropospheric temperatures but less influence upon the stratospheric temperatures than carbon dioxide. Temperature distribution in the troposphere is mainly accounted for by the presence of water vapour. Possible long term increases in the value of carbon dioxide do not affect the temperatures in the troposphere significantly.

2. The behaviour of ozone towards the radiative equilibrium is in same direction both in the troposphere and stratosphere. Unlike water vapour and carbon dioxide, an increase in ozone causes warming throughout the atmosphere and *vice versa*. The warm stratosphere is mainly accounted for by the presence of ozone.

3. Surface albedo and hence the ground temperature plays a very important role in fixing the temperature of the lower tropospheric levels.

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