COMPARISON AMONG VARIOUS NUMERICAL MODELS DESIGNED FOR COMPUTING INFRARED COOLING

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ABSTRACT

The scheme of computing the temperature change due to long wave radiation, developed by Manabe and Strickler and incorporated into the general circulation models developed at the Geophysical Fluid Dynamics Laboratory of ESSA, is compared with a group of other numerical schemes for computing radiative temperature change (e.g., the scheme of Rodgers and Walshaw). It is concluded that the GFDL radiation model has the accuracy comparable with other numerical models despite various assumptions adopted.

1. INTRODUCTION

Recently, Rodgers and Walshaw [20] proposed an improved method of computing the distribution of infrared cooling in the atmosphere. The major characteristics of their method as compared with the approach of radiation charts [4, 17, 25] are the subdivision of water vapor bands into many intervals and the use of a random model in representing the absorptivity curves.

The radiation model described by Manabe and Strickler [12] and Manabe and Wetherald [14] has been used at the Geophysical Fluid Dynamics Laboratory (GFDL) for the numerical studies of general circulation and the thermal equilibrium of the atmosphere during the past several years (see Smagorinsky et al. [22], Manabe et al. [13], Manabe and Hunt [15], and Hunt and Manabe [7] in addition to the papers cited above). Their method is essentially an adaptation of the traditional method of the radiation chart (i.e., Yamamoto [25], Elsasser [4], and Möller [17] chart) to the numerical method of computing radiative flux. Therefore, it is worthwhile to compare among the results which are obtained from these two schemes as well as some other numerical schemes (i.e., Plass [18, 19], and Hitchfeld and Houghton [5]). The model of Rodgers and Walshaw [20] has been programmed at GFDL in order to construct a general circulation model involving the upper atmosphere as well as the lower atmosphere. It was therefore possible to compare the performance of this model with those of other models.

2. CHARACTERISTICS OF THE MODELS

For the sake of simplicity, the following abbreviated symbols are used to identify various models:

(R-W) model—Rodgers and Walshaw [20];

(M-S) model*—Manabe and Strickler [12], Manabe and Wetherald [14];

(Plass) CO_2 model—Plass [19];

(Plass) O_3 model—Plass [18];

(H-H) O_3 model—Hitchfeld and Houghton [5];

(K) model—Kaplan [9].

(R-W) MODEL

The (R-W) model subdivides the 6.3-micron band, the rotation band, and the continuum of water vapor into 19 subintervals. Two of these subintervals contain the 15-micron carbon dioxide band and the 9.6-micron ozone absorption band. The transmissions of the two gases are multiplied together in these overlapping bands. A random model is used to represent the absorptivity for each subinterval. The Curtis-Godson approximation is used to estimate the effective pressure for absorption.

The random model fits very well the absorption band of water vapor. However, it fits poorly the 15-micron band of carbon dioxide. In figure 1a, solid lines show the absorptivity obtained by Burch et al. [2] from laboratory experiment. Dashed lines show the computed absorptivity based upon the random model. The mean line intensity and the mean half width, adopted for this computation, are determined theoretically (see table 6 of [20]). This figure shows that the agreement between the computed curves and the experimental curves is very poor. They coincide with each other only when pressure is low and accordingly, the degree of overlapping between the lines is small. The random model also fits very badly the ozone absorptivity, as shown by figure 1b. In this case the random model parameters were determined

*Improved version of the model constructed by Manabe and Möller [11].

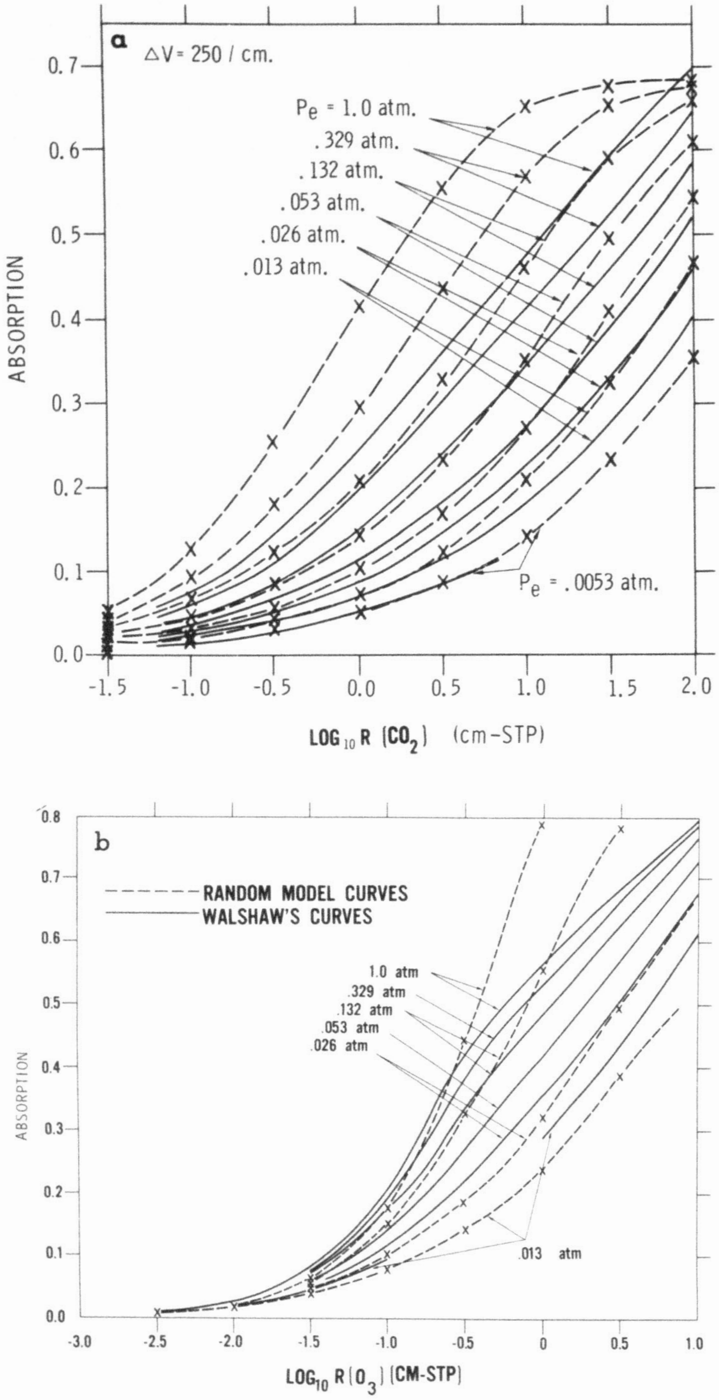

FIGURE 1.—(a) Carbon dioxide absorption. Solid curves observed by Burch et al. [2], dashed curves computed by random model. (b) Ozone absorption. Solid curves observed by Walshaw [24], dashed curves computed by random model.

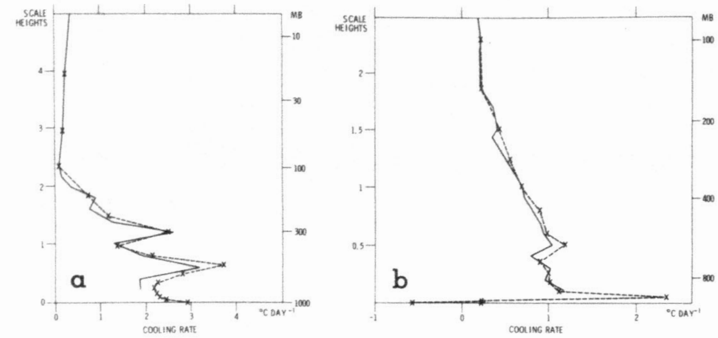

FIGURE 2.—Water vapor cooling rate of original Rodgers and Walshaw [20] model, solid lines, compared to GFDL version of (R-W) model, dashed lines: (a) tropical atmosphere; (b) Arctic atmosphere.

empirically using the least squares curve-fitting method of Rodgers and Walshaw [20] and the laboratory data of Walshaw [24]. In view of this poor agreement for both carbon dioxide and ozone, we programmed the following two versions of the (R-W) model:

$(R\text{-}W)_1$ Model: This model uses the random model absorptivity. The effect of the temperature dependence of line intensity is incorporated in the model as suggested by [20].

$(R\text{-}W)_2$ Model: Carbon dioxide absorptivity, which is measured by Burch et al. [2] under various pressures, is used for this model. The temperature dependence of this absorptivity is determined from the theoretical computation of Sasamori [21]. The ozone absorptivity determined by Walshaw [24] is used with no correction for temperature.

Both versions of the model described above differ slightly from the original model of Rodgers and Walshaw. Their original model computed cooling rates by means of a flux divergence equation, while our version does this computation by taking flux differences across each layer. The water vapor spectrum is divided slightly differently and the vertical spacing of levels is different in our versions of the model.

Our $(R\text{-}W)_1$ model was compared with the original (R-W) model for the case of cooling due to water vapor in a tropical atmosphere and an Arctic atmosphere. The results are shown in figures 2a and 2b, respectively, which correspond to figures 11d and 11e of [20]. The results are similar.

The computation time for an 18-level (R-W) model is about 1.5 sec. on the UNIVAC 1108 computer.

Earlier, a method very similar to the (R-W) model was proposed by McClatchey [16] for the computation of infrared cooling due to water vapor. There are minor differences between the two. For the rotation band of water vapor, McClatchey uses an empirically determined general transmission function instead of the random model transmission function. McClatchey's water vapor rotation band (50–680 cm.$^{-1}$) does not coincide with the (R-W) rotation band (0–960 cm.$^{-1}$), and McClatchey does not consider the continuum. To test the similarity of the two methods the (R-W) model was restricted to the same spectral interval that McClatchey used, and a cooling rate computation was made for one of the cases given in McClatchey's paper; the results were sufficiently similar, so we did not compare McClatchey's results with any of the other models.

(M-S) MODEL

For the computation of infrared cooling due to water vapor the mean transmissivity (or mean absorptivity), which is weighted with respect to the temperature derivative of the black body emission, is defined for the entire band as Yamamoto [25] suggested. The random model is used for the computation of mean transmissivity. The large temperature dependence of the mean absorptivity below 200° K. is considered for the flux computation by introducing the so-called emissivity at 220° K. The mean half width and mean line intensity are determined using the experiment of Howard et al. [6] and the theoretical computation of line intensity of Yamamoto. The continuum was treated as if it were a band with random model structure.

The absorptivity of the 15-micron band of carbon dioxide and that of the 9.6-micron band of ozone are determined using the results of laboratory measurement of absorptivity, which were carried out by Burch et al. [2] and Walshaw [24] under various pressures. See page 257 of Manabe and Wetherald [14] for the method of determining the absorption curve used for the computation. In order to estimate the temperature dependence of the absorptivity of the 15-micron band, the theoretical computation of the absorption by this band by Sasamori [21] is used. The temperature dependence of ozone absorption is neglected. The scaling approximation was used for incorporating the pressure effect.

Computation time for an 18-level (M-S) model is about 0.4 sec. on the UNIVAC 1108 computer, or about one-fourth the time of the (R-W) model.†

(PLASS) CO_2 MODEL AND (PLASS) O_3 MODEL

For the computation of infrared cooling due to the 15-micron band of carbon dioxide, the laboratory measurement of Cloud [3] is used. The band is subdivided into 1-micron intervals and the radiative flux divergence is computed for each interval. The effect of the temperature dependence of line intensity is taken into consideration. The two parameter-scaling approximation of pressure and optical thickness is used for treating the atmospheric inhomogenity.

For the computation of infrared cooling due to the 9.6-micron band of ozone, the results from the laboratory measurements of Summerfield‡ [23] are used. The effect of the temperature dependence of absorptivity is neglected.

(H-H) O_3 MODEL

The band model is not used. The Lorentz line shape is assumed. The smallest interval chosen (near the line center) is equal to the line width at 5-mb. pressure. The contribution of each subinterval to the infrared cooling is estimated. The treatment of the pressure effect is exact. The theoretical line strength of Kaplan, Migeotte, and Neven [8] is normalized upon Walshaw's [24] data, because their theory takes no account of severe Coriolis interaction.

†When the (M-S) model is used in the general circulation model [13], about 6 percent of the total computation time is used by the radiation program (assuming the long wave radiation computation is done four times per forecast day, which is sufficiently often, since it changes slowly with time).

‡The result of Summerfield [23] is quite different from that of Walshaw [24], which was obtained more recently.

(K) CO_2 MODEL

One of the most sophisticated numerical models has been proposed by Kaplan [9]. After dividing the absorption band into very narrow intervals of about 10/cm., the absorptivity is computed either by assuming a random model, or the Elsasser model and the multiplication properties for overlapped subband, whichever is appropriate. Pressure effects are included by the use of Curtis-Godson Approximation. The effect of temperature on the line intensity is incorporated exactly. It is probable that this model consumes 10–20 times as much computation time as (R-W) model. Therefore, this model is still not suitable for incorporation into the general circulation model.

3. COMPARISON OF RESULTS

(M-S) MODEL AND (R-W) MODEL

The vertical distributions of temperature, water vapor, and ozone, which are used for this comparison, are shown in figure 3. The exact values are given in table 1. For carbon dioxide a constant mixing ratio of 0.456 gm./kg. is used at all levels in the atmosphere. Figure 4 shows the cooling rate comparison for each of the absorbers and figure 5 shows the flux distribution when all three absorbers are present.

Water vapor—The agreement between the two results shown in figure 4 is excellent in the stratosphere and upper troposphere. There are some differences between the two results in the lower troposphere. This discrepancy is

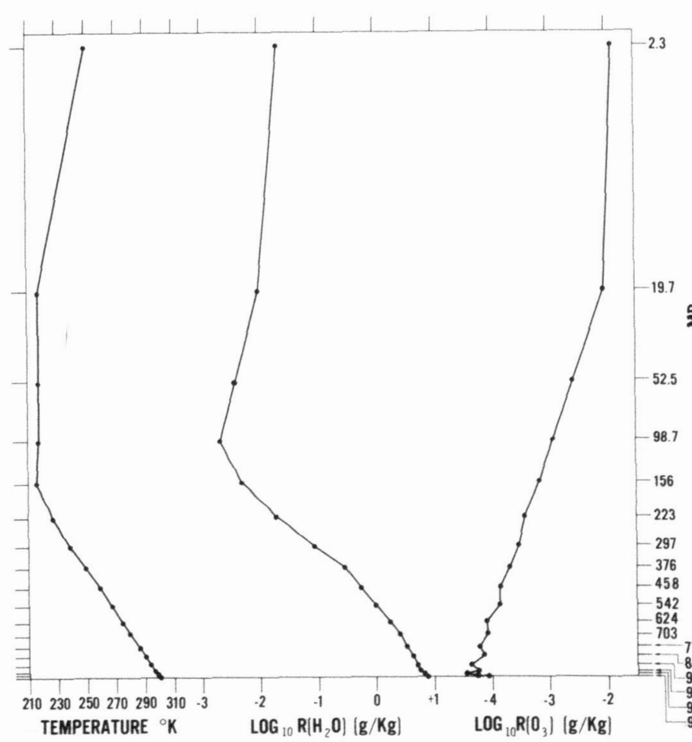

FIGURE 3.—Temperature, water vapor, and ozone distributions used for computations of figure 4.

TABLE 1.—*Values of temperature, water vapor, and ozone used for comparison of (M-S) model and (R-W) model*

Pressure (mb.)	Temperature (°K.)	Mixing Ratio (gm./kg.)	
		R (Water)	R (Ozone)
0.0000	251.3879	0.0000	0.000000
2.2719	251.3879	.0229	.012436
19.6759	218.1012	.0105	.009136
52.5120	218.5738	.0039	.002766
98.7226	218.0662	.0022	.001148
156.2500	215.9686	.0050	.000676
223.0367	226.7878	.0201	.000372
297.0250	239.2173	.0860	.000290
376.1574	250.0018	.2930	.000202
458.3762	259.4072	.5730	.000139
541.6238	267.6333	1.0400	.000139
623.8426	274.8176	1.7700	.000080
702.9750	281.0544	2.6400	.000085
776.9633	286.3196	3.4800	.000062
843.7500	290.8185	4.3700	.000071
901.2774	294.4844	5.2200	.000044
947.4880	297.3169	5.9700	.000058
980.3241	299.2888	6.5700	.000033
997.7281	300.3594	7.0000	.000094
1000.0000	300.3594	7.0000	.000094

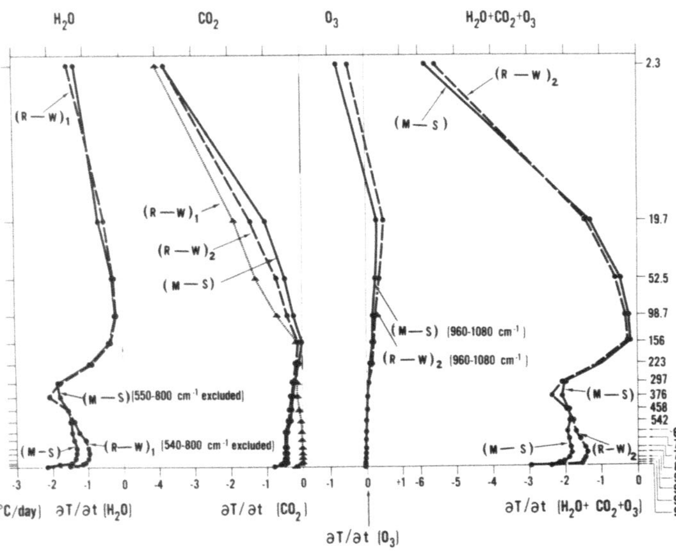

FIGURE 4.—Comparison of heating rates computed by the (M-S) and (R-W) models.

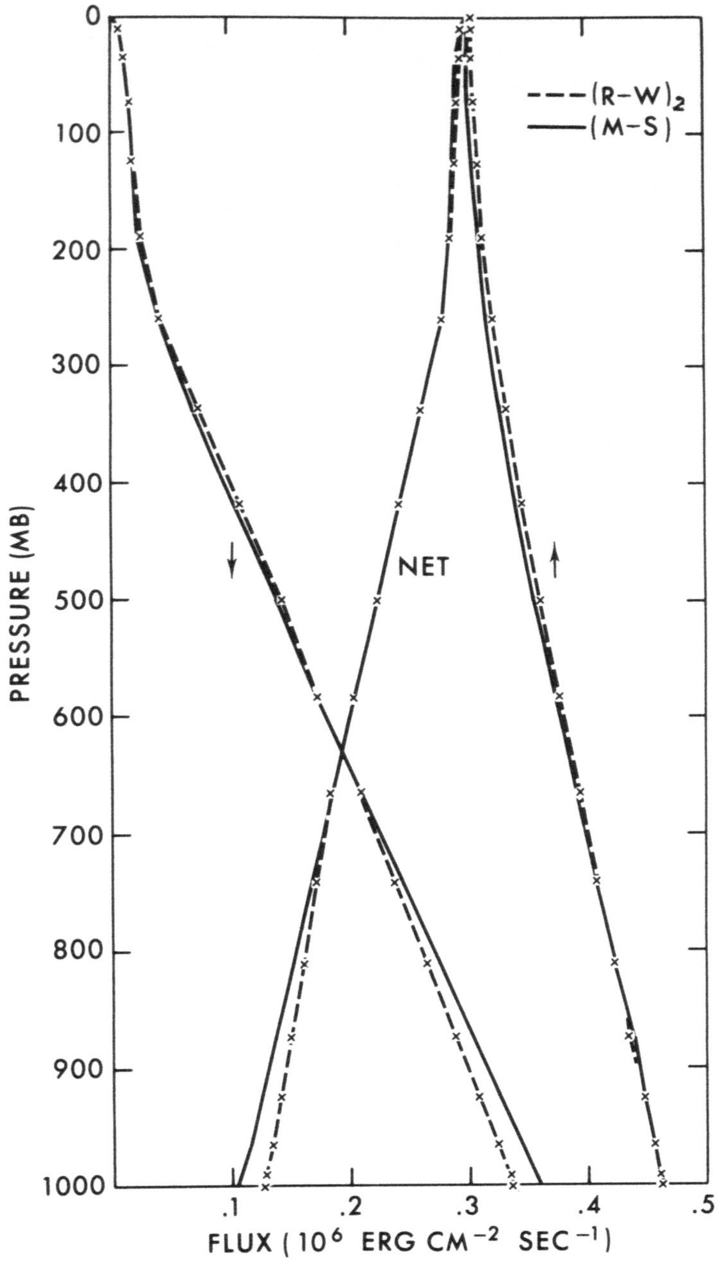

FIGURE 5.—Comparison of upward, downward, and net long wave radiation flux from (M-S) and $(R\text{-}W)_2$ models, with all three absorbers present.

partly caused by the different absorptivities used in the two models. These absorptivities are compared in figure 6; the solid curves are used in the (M-S) model and the dashed curves are from the (R-W) model. The absorptivities differ because mean half width and line intensity and the treatment of continuum are different. A comparison of the rotation band line intensities is given in figure 7. The (M-S) model uses the line intensities of Yamamoto [25], shown by the smooth curve, while the (R-W) model uses the line intensities of Benedict and Kaplan [1], the stepped curve. Figure 7 shows that the two intensities are significantly different. A series of test computations with the (R-W) model revealed that about 50 percent of the discrepancy in cooling rate in the lower troposphere (fig. 4) was due to these different line intensities. The remainder of the discrepancy is mostly due to the differences in the treatment of continuum and that of pressure effect.

Carbon dioxide—$(R\text{-}W)_1$ model yields practically no infrared cooling due to carbon dioxide in the troposphere (fig. 4). This unrealistic result is caused by the unrealistic absorptivity, which we have already discussed.

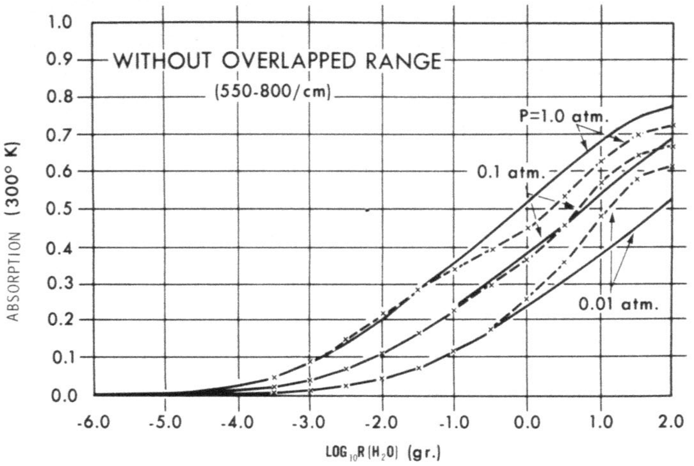

FIGURE 6.—Mean slab absorptivity of water vapor at temperature 300°K. Solid lines and dashed lines are obtained using the experimental results of Howard et al. [6] and the theoretical results of Benedict and Kaplan [1] respectively. The contribution from the wave number range 550–/cm. is not included for this computation.

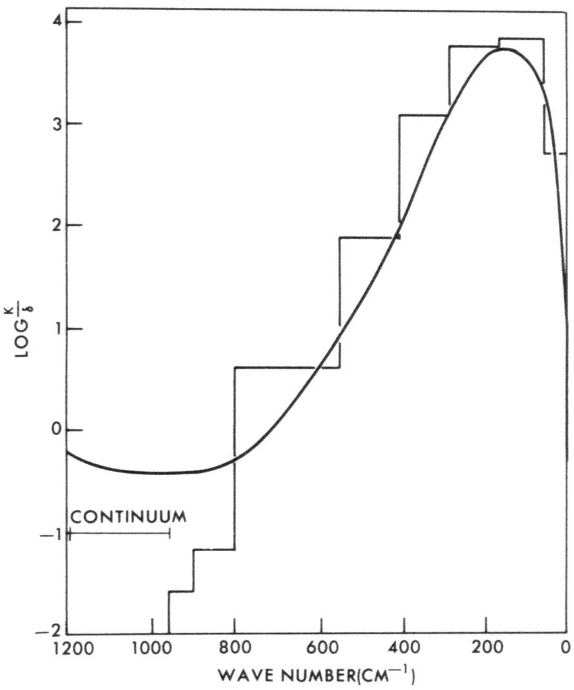

FIGURE 7.—Line intensities for the water vapor rotation band. Smooth curve due to Yamamoto [25], stepped curve computed from Benedict and Kaplan [1] data, for temperature 260°K.

The agreement between the results from the $(R\text{-}W)_2$ model and that from the (M-S) model is reasonably good.

Ozone—The agreement between the results from the $(R\text{-}W)_2$ model and those from the (M-S) model is fair (fig. 4). This difference is mainly caused by the difference between the Curtis approximation and the scaling approximation used for the (M-S) model. This was verified by substituting the scaling approximation for the Curtis

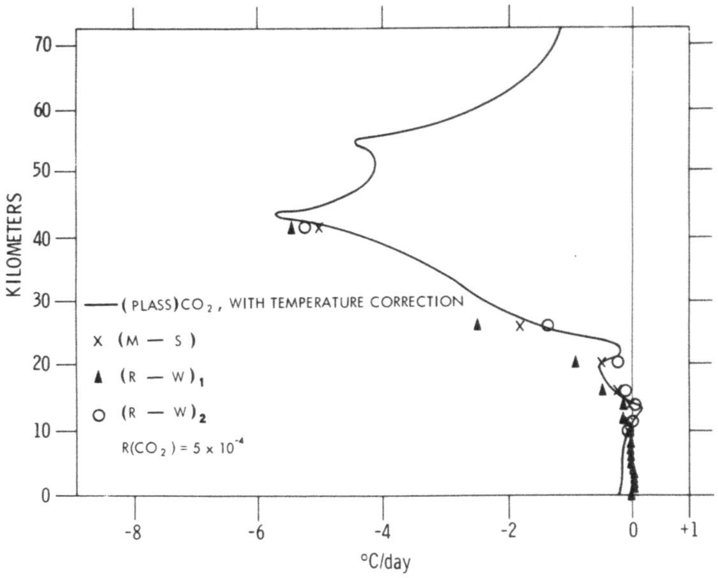

FIGURE 8.—Carbon dioxide heating rate of Plass [19] compared with other models. The (M-S) and $(R\text{-}W)_2$ results are identical with Plass in the lower 10 km., but are not plotted.

approximation in the (R-W) model. The scaling factor of (M-S) model is 0.3 for ozone. This resulted in a heating rate much closer to that of the (M-S) model.

Water vapor plus carbon dioxide plus ozone—The agreement is good except for the minor difference in cooling rate in the lower troposphere (fig. 4). This difference in cooling rate is consistent with the flux distribution of figure 5; net flux of the $(R\text{-}W)_2$ model is about 20 percent larger than that of the (M-S) model at the 1000-mb. level. The flux differences at high pressures are caused by the different water vapor absorptivities (fig. 6) used in the two models, as already discussed.

(PLASS) CO_2 MODEL AND OTHER MODELS

According to figure 8 the agreement among the results from (Plass) CO_2 model, from the (M-S) model, and from the $(R\text{-}W)_2$ model is excellent. The result from the $(R\text{-}W)_1$ model agrees with other results only at higher levels where the pressure is low and overlapping between lines is small.

(H-H) O_3 MODEL AND OTHER MODELS

Figure 9 shows that the agreement among the results of the (H-H) O_3 model and other models is fair. Again, the difference between the result from the (M-S) model and that of the $(R\text{-}W)_2$ model is mainly caused from the difference in the treatment of the pressure effect on the ozone absorption. It is interesting that the (M-S) model approximates the (H-H) model a little better than the $(R\text{-}W)_2$

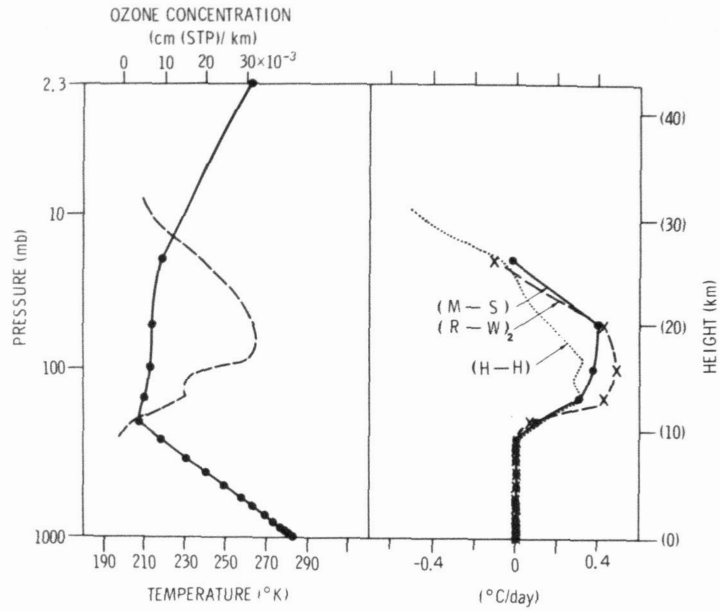

FIGURE 9.—Ozone heating rate of Hitchfeld and Houghton [5] compared with other models. In left portion, solid curve is temperature profile and dashed curve ozone distribution.

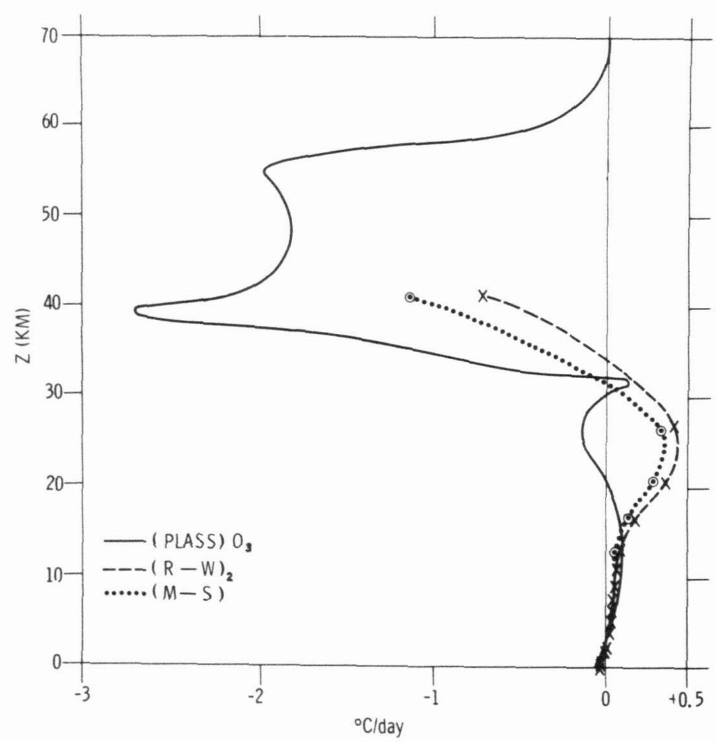

FIGURE 10.—Ozone heating rate of Plass [18] compared with other models. (M-S) and $(R\text{-}W)_2$ are identical in the lowest 10 km.

TABLE 2.—*Difference in net flux (erg cm.$^{-2}$sec.$^{-1}$)*

	Top	Bottom
$(R\text{-}W)_2$	3946	5200
(M-S)	3900	5300
(K)	3497	4889

model. Although it is probable that the scaling approximation is more accurate for this band than the Curtis-Godson approximation, we can not conclude so convincingly, because of the ambiguity involved in the determination of line intensity for (H-H) model.

(PLASS) O_3 MODEL AND OTHER MODELS

Figure 10 shows that the results obtained from the (M-S) and $(R\text{-}W)_2$ models are quite different from Plass' results. This is mainly due to the difference between the absorptivity of Summerfield [23] and that of Walshaw [24].

(K) CO_2 MODEL AND OTHER MODELS

Unfortunately, the example of the computation of temperature change, which is obtained by the (K) model, is not available to us. Using this model, Kaplan [10] estimated the dependence of net flux on the amount of carbon dioxide present in the atmosphere. In table 2, his results for a cloudless atmosphere, surface temperature 0°C., lapse rate 5.7°C./km., are compared to the changes in net flux obtained from the $(R\text{-}W)_2$ and (M-S) models. The values in table 2 are the difference in net flux at the top and bottom of the atmosphere when the carbon dioxide amount is changed from 130 cm. STP to 260 cm. STP. Though the dependence on carbon dioxide amount which is obtained by the (K) model is somewhat smaller than that obtained by the other two models, the agreement among the results is good.

4. CONCLUSION

The vertical distributions of the rate of temperature change due to the long wave radiation, which are obtained using the variety of methods, are compared with each other.

Generally speaking, the results from the Manabe-Strickler model agree reasonably well with those from the Rodgers and Walshaw model, or the Plass CO_2 model, despite the scaling approximation which is adopted for the (M-S) model.

There are some minor discrepancies among the results of the various authors, particularly among the computations of the effect of the 9.6-micron band of ozone.

In conclusion, the scheme of computing radiative transfer that is incorporated into the general circulation models of GFDL has comparable accuracy with other schemes despite various simplifications which are adopted for the model.

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