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The Overlapping of Cloud Layers in Shortwave Radiation Parameterizations

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ABSTRACT

Using the shortwave radiation scheme of Fouquart and Bonnel that accounts for scattering and absorption by gases and cloud particles, we study the effect of varying the assumption for the overlap of partially cloudy layers, and the resultant impact upon the heating rate profile, planetary albedo, net flux at the surface, and atmospheric net absorption. In this study, we consider the maximum, minimum, and random overlap assumptions and a radically simple scheme to approximate the radiative effects of a random overlapping of clouds. This simple scheme involves linear combinations of clear and cloudy reflectivities and transmissivities within a layer, and gives, respectively, fluxes and heating rates with maximum differences of 5% and 0.1 K day^{-1} compared to similar quantities obtained from a full calculation assuming a random overlapping of cloud layers. This former approach, however, is much more time efficient (five times faster for a 3-cloud atmosphere, three times faster in a full-size GCM).

Compared to the random assumption, the maximum overlap assumption gives smaller planetary albedo and larger net flux at the ground, whereas larger planetary albedo and smaller net flux at the ground result from the minimum overlap assumption. These differences tend to smooth out for larger values of the surface reflectivity. Systematic differences in the radiative forcings of a GCM due to these different cloud overlap assumptions largely vary with the cloud generation scheme.

1. Introduction

Over the recent years, various radiation schemes have been developed, the accuracy and computational efficiency of which have made them suitable for computing the radiative fluxes and related heating/cooling rates in large-scale numerical models of the atmosphere. Stephens (1984) has reviewed the various methods presently used in some existing GCMs, and discussed the various parameterizations for the absorptions by water vapor, carbon dioxide, oxygen, ozone, and for the scattering and absorption associated with clouds and hazes. He addressed briefly the problem of partial cloudiness occurring in multilayered atmospheres, and concluded that, due to the lack of rigorous test calculations, it is difficult to assess the relative merits of the different assumptions customarily used to treat cloud overlap. This paper concentrates on this particular aspect of shortwave radiation parameterizations, in the context of plane parallel clouds. We present results of computations carried out with the shortwave radiation scheme of Fouquart and Bonnel (1980), in which we have assumed different cloud overlaps, namely, the random overlap, the minimum overlap, the maximum overlap, and the linear combination of layer transmissivities and reflectivities present in the original formulation of this radiation scheme. Hereafter, these different cloud overlap assumptions will be referred to as RANDOM, MINIMUM, MAXIMUM, and SUNRAY, respectively. The scheme and the modifications implied by this study are presented in section 2. We show in the following sections how the various assumptions for the cloud overlap impact the heating rate profile, planetary albedo, net flux at the surface, and total atmospheric absorption for the cases of two and three overlapping cloud layers of varying horizontal cover. In section 3, we compare results obtained with either SUNRAY or RANDOM assumption, and show that SUNRAY mimics quite accurately, but more efficiently, the effects of a random overlapping of the cloud layers. In section 4, similar comparisons are made for RANDOM and either MINIMUM or MAXIMUM assumptions. In section 5, results are shown for the case of the radiation fields computed by a GCM (NCAR Community Climate Model), followed by a discussion of the implications of our study for climate modeling.

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2. The cloud overlap schemes

Different ways of dealing with cloudiness occurring in multilayered atmospheres are presently used in existing GCMs; the most used are the random and the maximum (or complete) overlap assumptions, neither of which is completely justifiable from observations of the actual atmosphere. In fact, the appropriate overlap assumption to use should depend on the spatial scale considered: for example, when the spatial scale is large enough to contain more than one synoptic situation in a grid box, one should probably assume minimum overlap as the cumulus forming in one corner of a 500-km grid box will probably not overlap the cirrus formed in a distant part of the box. In the random overlap assumption, all cloud layers are independent of one another; in the maximum overlap assumption, cloud layers lay above one another so that they maximize their common parts, whereas, in the minimum overlap assumption, cloud layers lay apart from one another so that they minimize their common parts. Hence, it is interesting to quantify the differences introduced by these three different assumptions.

In all cases, calculations are carried out in two steps: first, the radiative fluxes are computed for each of the vertical cloud distributions allowed by the overlap assumption assuming layers of overcast clouds; second, those fluxes are combined linearly according to the fractions of the sky they are supposed to cover for a given cloud overlap assumption.

With the random overlap assumption, an atmosphere containing three cloud layers, low, medium, and high, with fractional cover C_l, C_m, and C_h, respectively, can be divided into eight fractions corresponding to different distributions of the cloud layers, namely, a clear fraction, C_{clr}, three fractions with only one cloud layer, C_j^1, three fractions with two overlapping cloud layers, C_{ij}^2, and a fraction, C^3, where the three cloud layers are superimposed. Corresponding horizontal fractions are given below:

$$C_{clr} = \prod_{i=1}^{3} (1 - C_i), \tag{1a}$$

$$C_j^1 = C_j \prod_{i \neq j}^{i=1,3} (1 - C_i), \tag{1b}$$

$$C_{ij}^2 = (1 - C_k)C_iC_j, \tag{1c}$$

$$C^3 = \prod_{i=1}^{3} C_i, \tag{1d}$$

where C_i, C_j or C_k stands for any of the fractional covers C_l, C_m and C_h.

With the minimum overlap assumption, a similar atmosphere containing the same three clouds can be divided into up to eight fractions, the values of which are

$$C_{clr} = 1 - \min(1, C_l + C_m + C_h), \tag{2a}$$

$$C_j^1 = \max(0, C_j - C_{ij}^2 - C_{jk}^2 - C^3), \tag{2b}$$

$$C_{ij}^2 = \max(0, C_i + C_j - 1), \tag{2c}$$

$$C^3 = \max(0, C_{ij}^2 + C_{jk}^2 + C_{ki}^2 - 1). \tag{2d}$$

With the maximum overlap assumption, a similar atmosphere containing the same three clouds can be divided into four fractions, the values of which are

$$C_{clr} = 1 - \max(C_l, C_m, C_h), \tag{3a}$$

$$C_j^1 = \max[0, C_j - \max(C_i, C_k)], \tag{3b}$$

$$C_{ij}^2 = \max[0, \min(C_i, C_j) - C^3], \tag{3c}$$

$$C^3 = \min(C_l, C_m, C_h). \tag{3d}$$

This last assumption allows a more efficient calculation as it requires the evaluation of a smaller number of radiative flux profiles (four instead of eight for a three-cloud atmosphere).

In the shortwave radiation scheme that Fouquart and Bonnel (1980) designed for the Laboratoire de Météorologie Dynamique GCM (the SUNRAY code), the authors have assumed that the effect of a cloud with horizontal cover C, in a given layer, can be simply introduced by weighting linearly the respective clear and cloudy reflectivities and transmissivities according to their fractions in the layer, i.e.,

$$R = (1 - C)R_{clr} + CR_{cdy}, \tag{4a}$$

$$T = (1 - C)T_{clr} + CT_{cdy}, \tag{4b}$$

where *clr* and *cdy*, respectively, refer to the clear and cloudy parts of the layer. Reflectivity and transmissivity in the clear-sky fraction of the layer are respectively given as

$$R_{clr} = (R_u + R_R(1 - R_u))T^{\uparrow}T^{\downarrow}, \tag{5a}$$

$$T_{clr} = (1 - R_R)T^{\downarrow}, \tag{5b}$$

where R_u is the reflectivity of the underlying (or the surface) layer, R_R is the reflectivity due to Rayleigh scattering, $T^{\uparrow}$ and $T^{\downarrow}$ are the transmissions for molecular absorption, $T^{\uparrow}$ is the upward-looking transmission of the clear-sky layer assuming diffuse radiation, and $T^{\downarrow}$ is the downward-looking transmission of the clear-sky layer assuming direct radiation propagating with an effective zenith angle μ_e which depends on the amount of cloudiness and optical thickness already encountered on its way between the top of the atmosphere and the top of the considered layer:

$$\mu_e = [(1 - CC)/\mu + 1.66CC]^{-1}, \tag{6a}$$

with

$$CC = 1 - \prod_i (1 - C_i\epsilon_i), \tag{6b}$$

and

$$\epsilon_i = 1 - \exp\left(-\frac{(1 - \omega_i g_i^2)\tau_i}{\mu}\right). \tag{6c}$$

In (6b), the product is carried out over all layers between the level under consideration and the top of the atmosphere; μ is the cosine of the solar zenith angle, and τ_i, ω_i, and g_i are, respectively, the optical thickness, single scattering albedo, and asymmetry factor of the cloud present in the ith layer; $(1 - CC)$ is the fraction of the layer that receives direct radiation, and ϵ is a correction factor accounting for the direct transmission of radiation through the cloud in the forward scattering peak.

In the present version of the scheme, R_{cdy} and T_{cdy} are evaluated with the Delta-Eddington approximation (Joseph et al., 1976), and for a given layer, both are dependent upon the reflectivity of the underlying layer (Shettle and Weinman, 1970).

While this method of accounting for the partial cloudiness clearly makes the overall reflectivity and transmissivity of a particular layer independent of the location of other clouds in any other layer, this approach does not truly correspond to the assumption of cloud layers overlapping randomly. Furthermore, reflectivities and transmissivities obtained by this linear weighting procedure can be thought to be poor, as the physical processes are known to be highly nonlinear. Comparisons with random overlap calculations will show in section 3 that there is good agreement between the two methods. It seems that the method could be applied with success to the adding-doubling technique, but we have not carried out the necessary tests.

In the following sections, we present results computed with the radiation scheme using these different cloud overlap assumptions that we will refer to as SUNRAY, RANDOM, MINIMUM and MAXIMUM, respectively. In the first case, the radiation scheme is used in its original format. In the three latter cases, calculations are carried out in two steps as discussed here.

We consider model clouds in the midlatitude summer (MLS) atmosphere of McClatchey et al. (1972). The low-level cloud is located in the 2–3 km layer, the medium-level cloud in the 5–6 km layer, and the high-level cloud in the 8–9 km layer. For all the clouds, ω and g are taken as 0.999 and 0.85 respectively, while low-, medium-, and high-level clouds are given an optical thickness of 20, 8, and 2 respectively. Calculations have also been performed for spectrally dependent values of ω and g derived from Wiscombe et al. (1984): differences in results for various cloud overlap assumptions are linked to the different geometrical distribution of clouds along the vertical, and conclusions presented hereafter are mainly independent of these two parameters. Calculations have been performed for cloudiness varying from 0 to 1 at different levels, with surface reflectivity A_s and cosine of solar zenith angle μ varying in the same range. For simplicity, A_s is independent of μ.

In other respects, the radiation scheme deals explicitly with a number of physical processes which are sometimes neglected or empirically parameterized in other equivalent schemes. It accounts for absorption by water vapor, oxygen, ozone, carbon dioxide, aerosols and cloud droplets. Multiple scattering by molecules (Rayleigh scattering), aerosols and clouds (Mie scattering) are treated in a rather explicit way. Interactions between scattering and molecular band absorption are dealt with by an extension of the photon path length distribution method (Irvine, 1964), which takes into account the scattering and absorption processes separately, with the gaseous absorption parameterized by means of Padé approximants.

3. Comparisons between SUNRAY and RANDOM results

a. Single cloud layer

We first present comparisons of the radiation fields obtained with SUNRAY and RANDOM in the case of a single cloud layer in the atmosphere. For RANDOM, we recall that calculations are done assuming a linear weighting of fluxes first calculated for either no cloud or an overcast cloud layer in the atmosphere, whereas SUNRAY calculations use a linear weighting of the reflectivities and transmissivities. Differences thus arise essentially from a slightly different equivalent zenith angle μ_e, which leads to small variations in the multiple scattering between the surface and the cloud layer. Tables 1 and 2 present the maximum relative differences [(SUNRAY − RANDOM)/RANDOM] for four different quantities, namely, the planetary albedo A_p, the net flux at the surface F_s, the total atmospheric absorption Abs, and the heating rate HR of the layer that contains the cloud, for three values of μ and four values of A_s representative of the whole range of atmospheric conditions, including a typical tropical situation ($\mu = 1.0$; $A_s = 0.1$) and a subarctic situation ($\mu = 0.1$; $A_s = 0.8$). Results are presented for both the cases of a low- and a high-level cloud. Absolute differences (SUNRAY − RANDOM) are also given in Table 1, for the low-level cloud case that has displayed the largest sensitivity to the cloud overlap assumption. Our computations show that both the absolute and relative differences between the two approaches are rather small for A_p, F_s, and Abs. Differences in the heating rate of the clear layers are negligible (<0.01 K day^{-1}), and differences in HR, although larger, remain of the order of 0.1 K day^{-1} in the worst case. Moreover, the midlatitude summer profile, with a rather large humidity content, tends to overestimate the heating rate, given the condition of insolation, more consistent with a subarctic atmosphere. Generally, differences in A_p, F_s, Abs and HR increase if μ decreases, or if A_s increases, consistently with discrepancies stemming from the different treatment of the multiple reflections between the surface and the cloud layer. Differences are also larger for a low- than for a high-level cloud, due to the

TABLE 1. Maximum differences between planetary albedo A_p, net flux at the surface F_s, total atmospheric absorption *Abs*, and heating rate of the layer including the cloud *HR*, computed by the radiation scheme using either SUNRAY or RANDOM assumptions for dealing with the partial cloudiness (see text).[*]

A_s	μ	A_p	F_s (W m^{-2})	*Abs* (W m^{-2})	*HR* (K day^{-1})
0.0	0.1	+0.7	−0.2	−1.1	+2.2
		(+0.002)	(−0.2)	(−0.7)	(+0.005)
	0.5	*N*	*N*	*N*	+0.4
		(+0.001)	(−0.02)	(−0.08)	(+0.005)
	1.0	*N*	*N*	*N*	+0.3
		(+0.001)	(−0.01)	(−0.02)	(+0.025)
0.1	0.1	−1.0	+0.3	−1.1	+8.4
		(−0.003)	(+0.3)	(−0.5)	(+0.012)
	0.5	−0.9	+0.2	*N*	+2.0
		(−0.002)	(+1.0)	(−0.07)	(+0.025)
	1.0	−0.6	+0.1	*N*	+0.8
		(−0.001)	(+1.0)	(−0.01)	(+0.030)
0.45	0.1	−4.2	+2.9	−1.1	+34.
		(−0.018)	(+2.3)	(−0.3)	(+0.06)
	0.5	−1.5	+1.0	*N*	+3.0
		(−0.006)	(+3.9)	(−0.05)	(+0.04)
	1.0	−0.6	+0.4	*N*	+0.9
		(−0.003)	(+2.9)	(−0.03)	(+0.02)
0.8	0.1	−5.6	+7.2	−1.1	+69.
		(−0.029)	(+4.3)	(−0.10)	(+0.10)
	0.5	−1.4	+2.3	*N*	+3.0
		(−0.008)	(+5.8)	(−0.02)	(+0.05)
	1.0	−0.4	+0.7	*N*	+0.7
		(−0.003)	(+3.6)	(−0.02)	(+0.03)

[*] Computations are made for the midlatitude summer atmosphere of McClatchey et al. (1972) including a low-level cloud layer located between 2 and 3 km with $\tau = 20$, $\omega = 0.999$, $g = 0.85$, and for some representative values of μ, the cosine of the solar zenith angle, and A_s, the surface reflectivity. Values between parentheses are absolute differences (in the corresponding units); other values are relative differences (%) with $|N| < 0.1$.

TABLE 2. Maximum differences between planetary albedo A_p, net flux at the surface F_s, total atmospheric absorption *Abs*, and heating rate of the layer including the cloud *HR*, computed by the radiation scheme using either SUNRAY or RANDOM assumptions for dealing with the partial cloudiness (see text).[*]

A_s	μ	A_p	F_s	*Abs*	*HR*
0.0	0.1	+3.1	−0.8	−1.1	+1.0
	0.5	+1.8	−0.2	*N*	+1.5
	1.0	+1.8	−0.1	*N*	+1.2
0.1	0.1	+2.2	−0.7	−1.1	+1.5
	0.5	+0.9	−0.2	*N*	+0.9
	1.0	+0.6	−0.1	*N*	+0.7
0.45	0.1	+0.4	−0.2	−1.1	+5.3
	0.5	−0.2	+0.1	*N*	+2.3
	1.0	*N*	*N*	*N*	+0.8
0.8	0.1	−0.6	+0.7	−1.1	+10.
	0.5	−0.4	+0.6	*N*	+4.5
	1.0	−0.1	−0.1	*N*	+1.2

[*] Computations are made for the midlatitude summer atmosphere of McClatchey et al. (1972) including a high-level cloud layer located between 8 and 9 km with $\tau = 2$, $\omega = 0.999$, $g = 0.85$, and for some representative values of μ, the cosine of the solar zenith angle, and A_s, the surface reflectivity. All values are relative differences (in percent) with $|N| < 0.1$.

more important reflectivity and absorptivity of an optically thicker cloud.

b. Two- and three-cloud layers

When two or more cloud layers are present in the atmosphere, differences between SUNRAY and RANDOM results also arise from the different treatment of the cloud overlap. Therefore, comparisons of results for a nonreflecting surface allow one to study more precisely that source of difference. The A_p is slightly overestimated at small values of C_l and C_h, but underestimated for $C_l < 0.4$ and $C_h > 0.8$; F_s is overestimated for all values of C_l and C_h for the larger values of μ, but is underestimated for $C_l < 0.2$ and $\mu = 0.1$. In any case, however, these differences never exceed 3.5%. Thus, errors directly linked to the SUNRAY treatment of cloud overlap are very small. Furthermore, when the surface is reflecting, these errors due to the overlap assumption are partly compensated as shown in Table 3, which presents relative differences in A_p,

TABLE 3. Maximum differences between planetary albedo A_p, net flux at the surface F_s, total atmospheric absorption *Abs*, and heating rates of the layers including a cloud HR_l and HR_h, computed by the radiation scheme using either SUNRAY or RANDOM assumptions for the cloud overlap (see text).[*]

A_s	μ	A_p	F_s	*Abs*	HR_l	HR_h
0.0	0.1	+2.8	+3.2	+0.9	−4.4	−10.
	0.5	−1.8	+2.0	+1.3	−1.5	−2.4
	1.0	−1.8	+0.9	+0.6	−1.1	−1.3
0.1	0.1	+1.9	+2.8	+0.8	−4.8	−29.
	0.5	−1.2	+1.6	+1.0	−1.4	−14.
	1.0	−1.1	+0.7	+0.4	−0.8	−8.5
0.45	0.1	+0.2	+1.4	+0.4	−8.6	−90.
	0.5	+0.6	+0.7	+0.9	+2.8	−42.
	1.0	+0.6	+0.2	−0.5	−1.8	−28.
0.8	0.1	+0.6	−1.0	+1.0	+70.	−160.
	0.5	−1.3	+0.2	+2.2	−4.8	−72.
	1.0	+0.9	+0.1	−1.4	−7.5	−51.

[*] Computations are made for the midlatitude summer atmosphere of McClatchey et al. (1972) including two cloud layers (a low-level cloud located between 2 and 3 km with $\tau = 20$, $\omega = 0.999$, $g = 0.85$, and a high-level cloud layer located between 8 and 9 km with $\tau = 2$, $\omega = 0.999$, $g = 0.85$), and for some representative values of μ, the cosine of the solar zenith angle, and A_s, the surface reflectivity. All values are relative differences (in percent).

F_s, *Abs* and heating rates in the cloud layers for three different values of A_s and μ. It must be noticed that even the largest relative differences in HR_l and HR_h in Table 3, which correspond to absolute differences as large as 1.6 K day^{-1} in the MLS atmosphere, would correspond to a difference below 0.1 K day^{-1} for the same clouds in the dry and cold subarctic winter profile of McClatchey et al. (1972) that would be more consistent with $\mu = 0.1$ and large A_s. Values of C_l and C_h for the maximum differences in A_p, F_s, and *Abs* depend on A_s and μ: they are generally between 0.35 and 0.75, with the lower values of C_l and C_h for the maximum differences in A_p, the higher values for the maximum differences in F_s, and values in-between for the maximum differences in *Abs*, HR_l and HR_h; these values tend to increase with A_s and to decrease with increasing μ.

The presence of a third (midlevel) cloud in the atmosphere also tends to decrease the differences in A_p and F_s between SUNRAY and RANDOM. These quantities are presented in Figs. 1a, b as they are calculated for the low- and high-level cloudiness varying between 0 and 1, assuming a random overlap of the cloud layers, for $\mu = 0.5$, $A_s = 0.45$ and a midlevel cloudiness $C_m = 0.25$. Maximum differences in A_p and F_s are 0.5 and 2.2%, respectively, and compensations between errors in the fluxes at the surface and at the top of the atmosphere give a maximum relative difference in *Abs* of 0.75%. As already indicated, differences in the heating rates in the atmospheric cloudy layers are larger, but correspond to absolute differences below 0.1 K day^{-1}, which are not very significant given the large uncertainties related to cloud optical properties and cloud cover as they are presently diagnosed in GCMs.

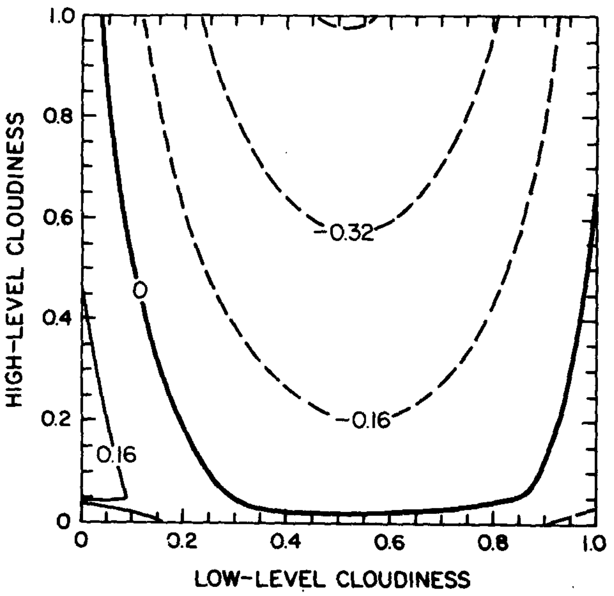

FIG. 1a. The relative difference (%) in planetary albedo between SUNRAY and RANDOM assumptions for cloud overlap. Calculations are performed for the midlatitude summer profile of McClatchey et al. (1972), with $\mu = 0.5$ and $A_s = 0.45$.

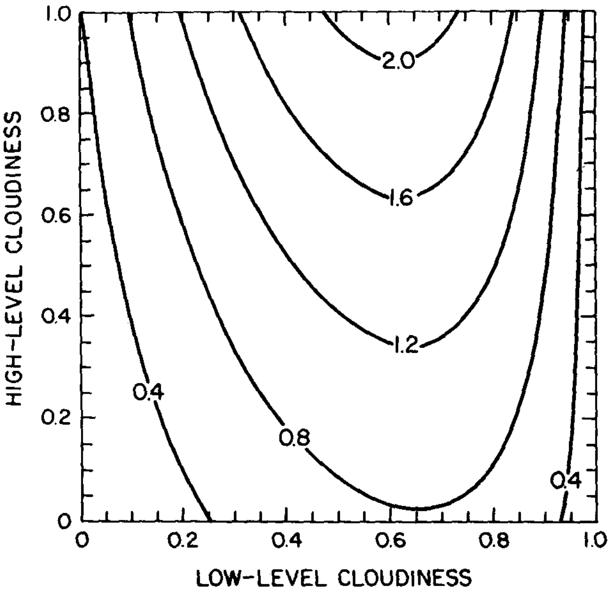

FIG. 1b. As in Fig. 1a, but for the net flux at the surface.

To sum up, the SUNRAY assumption for dealing with the overlapping of layers of partial cloudiness in GCMs is very attractive as it allows us to determine the shortwave components of the radiation budget of the atmosphere with a good accuracy (compared to the more usual way of assuming a random cloud overlap) but requires much less computational time; for example, for an atmosphere including three cloud layers, RANDOM carries out one "clear-sky" computation and seven sets of "cloudy" computations, while SUNRAY only needs one set of computations. As will be shown in section 5, the economy is particularly worthwhile in GCMs' computations where more than three cloud layers are often diagnosed by the model.

4. Comparisons between MAXIMUM, MINIMUM, and RANDOM results

While most of radiation codes presently used in GCMs assume a random overlap of partially cloudy layers (see Table 6 of Stephens, 1984), Ramanathan et al. (1983) have used the complete overlap assumption, and Geleyn and Hollingsworth (1979) have proposed an alternative which considers maximum overlapping of adjacent cloudy layers, but random overlapping of cloud parts separated by cloud-free layers. In order to assess what the maximum effect of such a treatment can be, we have carried out calculations of the radiative fields assuming only a maximum overlap of the different cloudy layers. Radiative fluxes and heating rates calculated under this MAXIMUM assumption are compared to RANDOM results for a two-cloud atmosphere and different conditions of insolation, and maximum relative differences are given in Table 4. From pure geometrical considerations, we expect the MAXIMUM A_p and F_s to be respectively smaller and larger than their RANDOM counterparts when the surface reflectivity A_s is low, and the reverse to be true for high values of A_s (when A_s becomes higher than the cloud albedos). Such an effect appears only indirectly in Table 4, where differences in A_p and F_s are large for $A_s = 0$, and decrease when A_s increases. The MAXIMUM A_p is smaller than the RANDOM A_p by as much as 11% for $A_s = 0$ and $\mu = 0.1$, and the difference decreases for higher values of A_s and/or when μ increases, indicating that the compensating mechanism is via the multiple reflections between the cloud layers and the surface. This effect tends to give a larger albedo to the smaller fraction of the sky which is covered by clouds. Similar effects can be seen with F_s with maximum difference of +25% decreasing when A_s and μ increase. Compensations between differences in the fluxes at the surface and at the top of the atmosphere give a maximum relative difference in *Abs* of 9%. Interestingly enough, the differences in the heating rates of the cloudy layers are smaller than in the comparisons between SUNRAY and RANDOM (see Table 3), and this fact is explained by larger differences (up to 0.1 K day^{-1}) occurring in the cloud-free layers of the atmosphere. For an atmosphere including three cloud layers, the differences in A_p and F_s tend to be smaller than for the two-cloud atmosphere.

Radiative fluxes and heating rates calculated under the MINIMUM assumption are compared to RANDOM results for a two-cloud atmosphere and different conditions of insolation, and maximum relative differences are given in Table 5. As expected, signs of the maximum relative differences in A_p, F_s, and *Abs* have switched relative to those in Table 4. MINIMUM A_p and F_s are, respectively, larger and smaller than RANDOM A_p and F_s, and the differences decrease with increasing A_s and increasing μ. By and large, larger differences are found for values of C_l and C_h such as $C_l + C_h = 1$ with maximum differences for $C_l = C_h = 0.5$. Moreover, maximum absolute differences for MINIMUM − RANDOM are larger than for MAXIMUM − RANDOM. As for the MAXIMUM − RANDOM comparisons, the differences in A_p and F_s are smaller in an atmosphere including three cloud layers.

TABLE 4. As in Table 3, but for comparison between MAXIMUM and RANDOM assumptions.

A_s	μ	A_p	F_s	*Abs*	HR_l	HR_h
0.0	0.1	−11.	+25.	+8.6	+6.1	−0.1
	0.5	−11.	+7.6	+5.2	−1.3	+1.2
	1.0	−8.8	+2.6	+2.1	−0.5	+2.6
0.1	0.1	−8.9	+24.	+7.7	+4.4	−0.6
	0.5	−7.7	+6.8	+4.5	−1.8	+1.3
	1.0	−4.9	+2.2	+1.7	−0.7	+1.7
0.45	0.1	−3.7	+18.	+4.3	−2.0	−2.4
	0.5	−2.1	+4.0	+2.2	−2.9	−1.1
	1.0	−0.6	+0.7	+0.4	−0.9	−1.9
0.8	0.1	−0.5	+12.	+0.8	−9.3	−4.6
	0.5	−0.1	+1.6	+0.2	−3.8	−4.3
	1.0	+0.1	−0.1	−0.2	−0.6	−7.8

TABLE 5. As in Table 3, but for comparison between MINIMUM and RANDOM assumptions.

A_s	μ	A_p	F_s	*Abs*	HR_l	HR_h
0.0	0.1	16.	−38.	−13.	42.	20.
	0.5	25.	−36.	−19.	40.	4.8
	1.0	42.	−36.	−22.	54.	5.5
0.1	0.1	14.	−37.	−12.	44.	20.
	0.5	20.	−34.	−18.	40.	5.2
	1.0	34.	−34.	−21.	51.	5.5
0.45	0.1	6.7	−31.	−7.8	54.	22.
	0.5	9.6	−30.	−13.	42.	7.7
	1.0	17.	−30.	−14.	51.	11.
0.8	0.1	1.6	−22.	−2.6	80.	26.
	0.5	1.7	−21.	−3.4	48.	16.
	1.0	2.3	−20.	−3.6	51.	25.

In any case, differences in A_p and F_s can be as high as 10 and 20%, respectively, for MAXIMUM − RANDOM; as high as 18 and 35 percent respectively for MINIMUM − RANDOM. Therefore, the assumption made for dealing with the overlapping of partially cloudy layers can be important inasmuch as it is the source of a systematic difference in the radiative forcing (in the deposition of energy at the ground level, for example), and thus leads to a modified response of a climate model.

5. Sensitivity of the NCAR-CCM shortwave radiative fields to cloud overlap assumptions

Given the original destination of the radiative scheme (i.e., computing the radiative fields for a GCM), it is important to study the effect of the different cloud overlap assumptions in the context for which the scheme has been designed. We have, therefore, introduced the radiation scheme and its various treatments for the cloud overlap into the NCAR Community Climate Model, and have carried out a series of one-time step calculations with either SUNRAY, RANDOM, MINIMUM, or MAXIMUM. In these calculations, cloudiness and cloud optics are internally generated by the model. A description of the cloud generation scheme can be found in Ramanathan et al. (1983). Cloud optical thickness τ and single scattering albedo

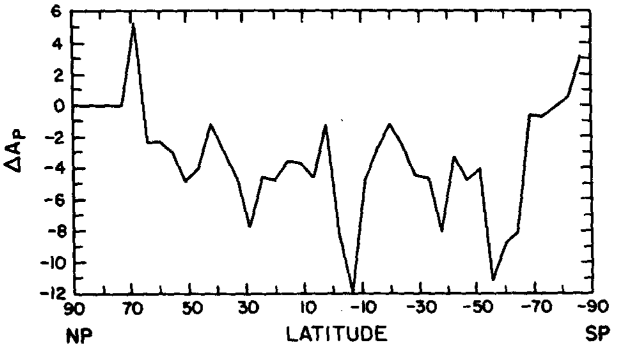

FIG. 2a. The zonal averages of the absolute difference in planetary albedo (multiplied by 10 000) between SUNRAY and RANDOM assumptions for cloud overlap. Calculations are performed for one time step of NCAR-CCM under January conditions.

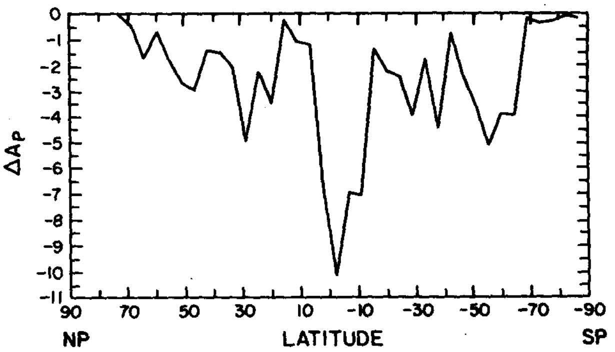

FIG. 3a. The zonal averages of the absolute difference in planetary albedo (multiplied by 1000) between MAXIMUM and RANDOM assumptions for cloud overlap. Calculations are performed for one time step of NCAR-CCM under January conditions.

ω are defined as functions of the liquid water content of the cloud, LWC, as in Fouquart and Bonnel (1980):

$$\tau = \frac{3LWC}{2r_e},$$

$$\omega = 0.9989 - 0.004\exp(-0.15\tau),$$

where r_e is an effective radius (in μm) for the cloud droplet distribution related to the liquid water density, LWD, as in Paltridge (1974);

$$r_e = 45LWD + 3.$$

The liquid water content of the clouds is obtained as in Charlock and Ramanathan (1985) from the model hydrological cycle, and is set as the rainout between two time steps. In case of RANDOM, MINIMUM and MAXIMUM calculations, (1), (2) and (3) are used, accordingly, to compute the fractions of the sky covered by the different cloud layers.

An almost perfect agreement between SUNRAY and RANDOM calculations is obtained with maximum local differences in A_p and F_s of −0.0112 and 6.35 W m^{-2}, respectively, corresponding to differences of −0.0012, and +0.72 W m^{-2} in zonal means (Figs. 2a, b). Such an agreement is also found with *Abs* and the heating rates, where the maximum differences in zonally averaged values are +0.60 W m^{-2} and 0.01 K day^{-1} respectively. Calculations of the shortwave radiative fluxes and heating rates for the 1920 columns (48 longitudes × 40 latitudes) of the NCAR-CCM are performed three times faster with the SUNRAY assumption than with the RANDOM assumption (3.6 s vs. 11.8 s).

Differences in A_p and F_s between MAXIMUM and RANDOM (−0.0968 and +48.8 W m^{-2} for the maximum differences, −0.01 and +4.5 W m^{-2} in zonal means in Figs. 3a, b), and between MINIMUM and RANDOM (+0.1221 and −77.9 W m^{-2} for the maximum differences, +0.09 and −7.4 W m^{-2} in zonal means), although larger than those between SUNRAY and RANDOM, remain rather small compared to the larger differences obtained from calculations in section 4. Such a behavior is explained by the larger number of clouds that can occur in a column (up to five cloudy layers are possible), and by the way the cloudiness is generated in the model. The cloud scheme affects fixed areal coverage to both convective and stratiform clouds (0.30 and 0.95 respectively). As seen in section 4, max-

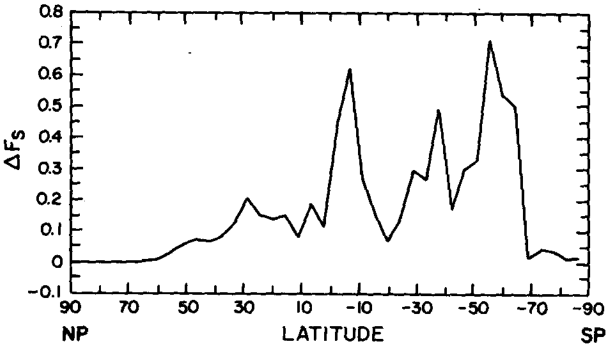

FIG. 2b. As in Fig. 2a, but for the absolute difference in net flux at the surface (W m^{-2}).

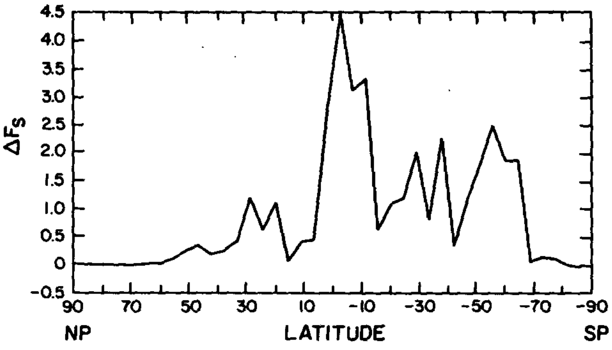

FIG. 3b. As in Fig. 3a, but for the absolute difference in net flux at the surface (W m^{-2}).

imum differences MAXIMUM − RANDOM are more likely to occur for small values of the cloudiness, whereas maximum differences MINIMUM − RANDOM appear when $\Sigma C_i = 1$ with all C_i equal. Thus, this cloud generation scheme tends to underestimate the differences linked to the different cloud overlap assumptions.

6. Conclusions

Using the shortwave radiation scheme of Fouquart and Bonnel (1980), we have studied the sensitivity of derived shortwave radiation fields to different cloud overlap assumptions. The SUNRAY assumption which gives the reflectivity and transmissivity of a partly cloudy layer as a linear function of the clear and overcast reflectivities and transmissivities is shown to be a very efficient means to account for partial cloudiness. With the help of comparisons carried out for a model atmosphere with either one, two or three clouds, as well as in the NCAR-CCM, planetary albedo, net flux at the surface, and heating rate in the atmosphere calculated with this assumption are shown to be in very good agreement with the results of the scheme incorporating a full treatment of the random overlapping. Maximum differences of 5% and 0.1 K day^{-1} on fluxes and heating rates, respectively, between the two approaches are at least an order of magnitude less than those that would arise from a 10% change in the cloud optical properties. Moreover, the former approach leads to large savings in computational time, inasmuch as it needs only one set of computations.

Similar comparisons are conducted for the maximum and minimum overlap assumptions. We show that, for a three-cloud atmosphere, differences between the maximum and random overlap assumptions remain below 20%, that differences between the minimum and random assumptions can be as high as 35%, that compensations occur between the clear and cloudy fractions of the sky which tend to smooth out the differences due to the different geometrical distributions, and that, in a GCM, the differences due to the cloud overlap assumption can be offset by the geometrical properties assigned to the clouds by the cloud generation scheme. However, the differences in the shortwave radiative forcings due to different overlap assumptions, if they are not compensated by similar differences in longwave radiative forcings, are likely to induce modifications in the response of the GCM, were it to be integrated over a longer period of time, but this question is beyond the scope of this paper.

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REFERENCES

Charlock, T. P., and V. Ramanathan, 1985: The albedo field and cloud radiative forcing produced by a general circulation model with internally generated cloud optics. *J. Atmos. Sci.* **42**, 1408–1429.

Fouquart, Y., and B. Bonnel, 1980: Computations of solar heating of the Earth's atmosphere: A new parameterization. *Beitr. Phys. Atmos.*, **53**, 35–62.

Geleyn, J.-F., and A. Hollingsworth, 1979: An economical analytical method for the computation of the interaction between scattering and line absorption of radiation. *Contrib. Atmos. Phys.*, **52**, 1–16.

Irvine, W. M., 1964: The formation of absorption bands and the distribution of photon optical paths in a scattering atmosphere. *Bull. Astron. Inst. Netherlands*, **17**, 266–279.

Joseph, J. H., W. J. Wiscombe and J. A. Weinman, 1976: The Delta-Eddington approximation for radiative flux transfer. *J. Atmos. Sci.*, **33**, 2452–2459.

McClatchey, R. A., R. W. Fenn, J. E. A. Selby, F. E. Volz and J. S. Garing, 1972: Optical properties of the atmosphere, 3rd ed., AFCRL-72-0497, 108 pp. [NTISN7318412].

Paltridge, G. W., 1974: Infrared emissivity, shortwave albedo and the microphysics of stratiform water clouds. *J. Geophys. Res.*, **79**, 4053–4058.

Ramanathan, V., E. J. Pitcher, R. C. Malone and M. L. Blackmon, 1983: The response of a spectral general circulation model to refinements in radiative processes. *J. Atmos. Sci.*, **40**, 605–630.

Shettle, E. P., and J. A. Weinman, 1970: The transfer of solar irradiance through inhomogeneous turbid atmospheres evaluated by Eddington's approximation. *J. Atmos. Sci.*, **27**, 1048–1055.

Stephens, G. L., 1984: The parameterization of radiation for numerical weather prediction and climate models. *Mon. Wea. Rev.*, **112**, 826–867.

Wiscombe, W. J., R. M. Welch and W. D. Hall, 1984: The effects of very large drops on cloud absorption. Part I: Parcel methods. *J. Atmos. Sci.*, **41**, 1336–1355.