LONG WAVE RADIATION FLUXES IN A PARTIALLY CLOUDY ATMOSPHERE

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ABSTRACT

The emissivity method of ELSASSER and CULBERTSON (1960) for the determination of infrared fluxes outside the atmospheric window in its modified form (ZDUNKOWSKI et al. 1966), ZDUNKOWSKI and BRESLIN (1979) is extended to include the effects of grey clouds. This is accomplished by introducing a grey transmission function for cloud droplets so that clouds no longer need to be treated as black bodies. In order to handle partial cloudiness, a column scheme is constructed based upon random overlap for isolated cloudy layers and maximum overlap for continuous cloudy layers. For the black-body approximation the column scheme turns into a one-column integration problem with horizontally varying integration limits. Computational results show that the model is able to simulate realistic situations of partial cloudiness. Radiative flux divergences at cloud tops and bases, as well as in the interior of thin clouds, as computed from the grey model produce much more realistic results than black clouds. If the clouds are thick enough ($\sim$ 500 m) the black-body approximation is acceptable.

1. INTRODUCTION

Any computational method for long wave radiative fluxes suitable for use in atmospheric circulation models should include the following processes:

- Band absorption: water vapour (6.3 μm band, rotational band) carbon dioxide (15 μm band), ozone (9.6 μm band), and trace gases, if necessary.
- Continuum absorption and e-type absorption of water vapour as well as aerosol absorption in the atmospheric window (8.75 - 12.25 μm).
- Cloud effects; while inside the window the treatment of scattering and absorption in clouds is mandatory, the question arises if this detailed treatment needs to be extended to the entire infrared spectrum.
- Finally, partial cloudiness should be taken into account which considerably influences the energy budget of the atmosphere and the earth's surface.

The following considerations are confined to the spectral region outside the window, since the window region is treated by a procedure which is nearly identical to the two-stream method proposed by EMCWF (GELEYN, 1977; GELEYN and HOLLINGSWORTH, 1979).

2. MODEL CHARACTERISTICS

Conventional radiation models usually include band absorption by H_2O and CO_2 and treat clouds as black bodies outside the window. In most cases the atmosphere is either treated as cloud-free or with 100 percent cloud cover using simple scaling if required. The aim of this investigation is to introduce non-black clouds as well as partial cloudiness into our radiation scheme. Attempts shall be made to obtain the conditions for which the black body approximation is reasonable. We require in the improved model that the basic conception of the radiative scheme remains unchanged, that the computing time is not increased excessively, and that partial cloudiness produces realistic results.

Our basic model is the emissivity method of ELSASSER and CULBERTSON(1960) in the modified form of ZDUNKOWSKI et al. (1966).

Its main characteristics are the decoupling of temperature and absorbing amount in the flux transmission function, the introduction of empirical, temperature-dependent spectral absorption coefficients, and the establishment of emissivity tables which may be evaluated graphically (radiation chart) or numerically in order to determine the radiative fluxes. The upward and downward flux equations are (i = reference level, i = 1(surface), ..., N(top of the atmosphere)):

$$F_i^{\uparrow} = B(T_{i_t}) - \int_{T_i}^{T_{i_t}} \left[R^*(u(T)-u(T_i),T) + \Delta R^*(u(T)-u(T_i),u'(T)-u'(T_i),T)\right] dT \qquad (1)$$

i_t = subscript of the nearest cloud top below the reference level, or i_t = 1, if no cloud is present

$$F_i^{\downarrow} = \delta_c B(T_{i_b}) + (1-\delta_c) \int_0^{T_N} \left[R^*(u(T_i),T) + \Delta R^*(u(T_i),u'(T_i),T)\right] dT + \int_{T_{i_b}}^{T_i} \left[R^*(u(T_i)-u(T),T) + \Delta R^*(u(T_i)-u(T),u'(T_i)-u'(T),T)\right] dT \qquad (2)$$

i_b = subscript of the nearest cloud base above the reference level, or i_b = N, if no cloud is present

$$\delta_c = \begin{cases} 0, & \text{if no cloud exists above the reference level} \\ 1, & \text{otherwise} \end{cases}$$

The quantity B(T) is the black-body flux, T the temperature, R^* the water vapour emissivity, ΔR^* the H_2O-CO_2 overlap emissivity, and u and u' stand for the reduced absorbing amounts of H_2O and CO_2. At a level inside a cloud we require:

$$F_i^{\uparrow} = F_i^{\downarrow} = B(T_i) \quad ; \quad F_{net} = F_i^{\uparrow} - F_i^{\downarrow} = 0 \qquad (3)$$

When clouds are no longer treated as black bodies, a continuous cloud transmission function τ_{H_2O} must be introduced. The total transmission function is the product of the individual transmission functions of water vapour, carbon dioxide and cloud droplets. If grey absorption for clouds is assumed, the droplet transmission function depends only upon the liquid water content but not upon wavelength and is therefore excluded from spectral integrations. Equations (1), (2), (3) now transform into (JAGOUTZ, 1980; PANHANS, 1980b):

$$F_i^{\uparrow} = B(T_1) - \int_{T_i}^{T_1} (1-\tau_{H_2O}(w(T)-w(T_i)) \frac{dB}{dT} dT -$$

$$- \int_{T_i}^{T_1} \tau_{H_2O}(w(T)-w(T_i)) \left[R^*(u(T)-u(T_i),T) + \Delta R^*(u(T)-u(T_i), u'(T)-u'(T_i),T)\right] dT \qquad (4)$$

$$F_i^{\downarrow} = (1-\tau_{H_2O}(w(T_i)))B(T_N) + \int_{T_N}^{T_i} (1-\tau_{H_2O}(w(T_i)-w(T))) \frac{dB}{dT} dT +$$

$$+ \tau_{H_2O}(w(T_i)) \int_0^{T_N} \left[R^*(u(T_i),T) + \Delta R^*(u(T_i), u'(T_i), T)\right] dT + \qquad (5)$$

$$+ \int_{T_N}^{T_i} \tau_{H_2O}(w(T_i)-w(T)) \left[R^*(u(T_i)-u(T),T) + \Delta R^*(u(T)-u(T_i), u'(T)-u'(T_i),T)\right] dT$$

where w is the optical depth of liquid water.

3. PARTIAL CLOUDINESS

Let us now proceed to the problem of partial cloudiness and consider a prognistic model grid point representative of a ceratin horizontal region. We have, in general, no information in which part of the region the clouds are situated, but the cloud fraction of every layer can be derived from the moisture field (e.g. SMAGORINSKY, 1960). From these cloud fractions we may construct the cloud scene above and below the reference level by means of reasonable assumptions as will be fully explained in Section 4.

An example is given in Figure 1. Several model levels in the vertical direction and two clouds extending over three sublayers with different cloud fractions are shown. Note that the abscissa is not a horizontal coordinate but the area fraction from 0 to 1.

Let us assume that the cloud scene has already been constructed. Reference level is i = 9. We divide the atmosphere into a number of columns which differ from each other with respect to cloud cover and water vapour since saturation exists inside the cloud while the cloud-free portion of every layer is unsaturated.

In this example, every single column consists of totally cloudy and cloud-free layers. We now apply Equations (4) and (5) for every column. The resulting fluxes are $F_{i\ell}^{\uparrow}$, $\ell = 1, \ldots, L$, and $F_{ik}^{\downarrow}$, $k = 1, \ldots K$, where L and K are the number of columns below and above the reference level i, respectively. The total upward and downward fluxes are linear combinations of the column fluxes:

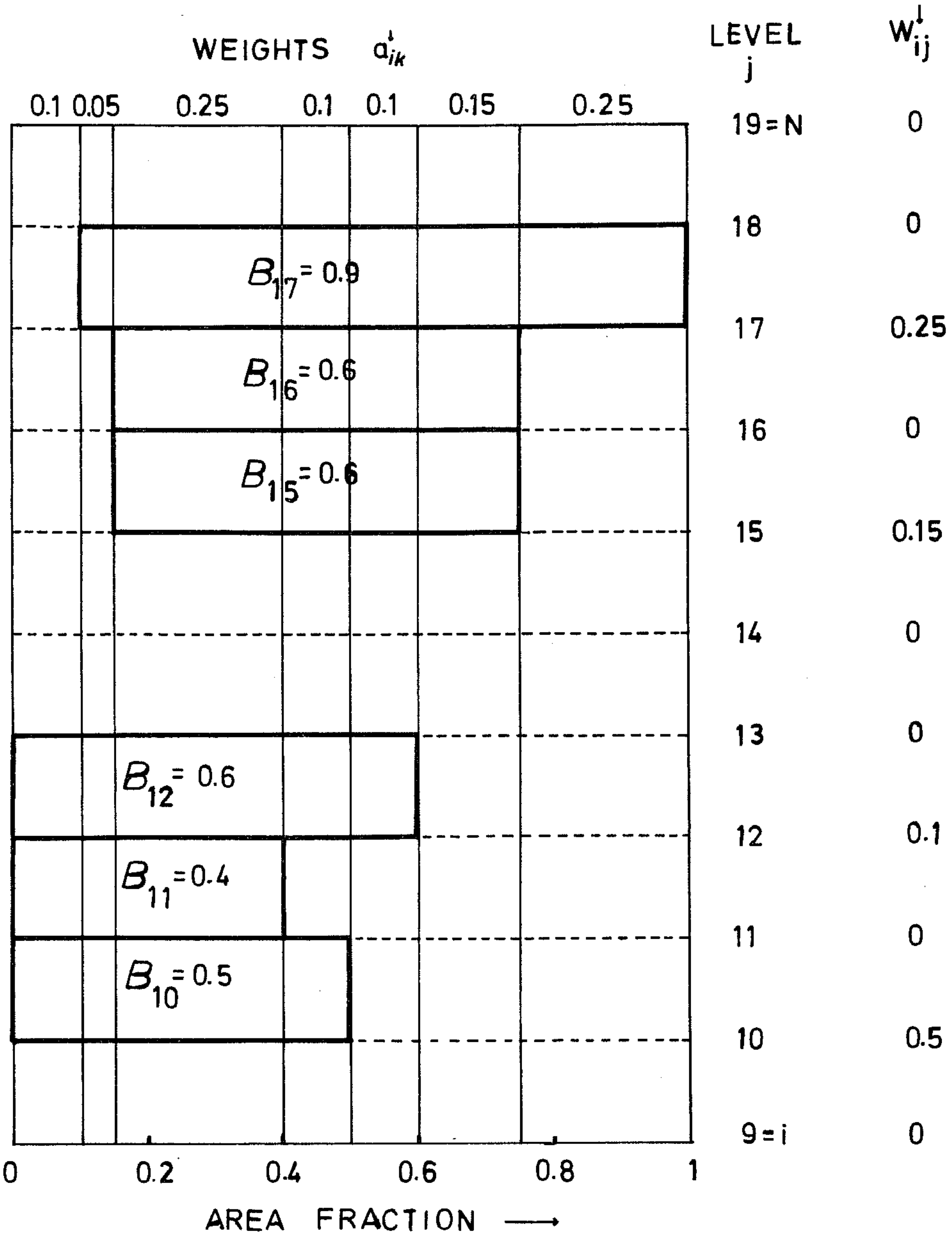


Figure 1. Cloud scene and column arrangement above the reference level. B_j = cloud fraction in layer j

$$F_i^{\uparrow} = \sum_{\ell=1}^{L} a_{i\ell}^{\uparrow} F_{i\ell}^{\uparrow} \quad ; \quad F_i^{\downarrow} = \sum_{k=1}^{K} a_{ik}^{\downarrow} F_{ik}^{\downarrow} \tag{6}$$

The weighting factors $a_{i\ell}^{\uparrow}$ and $a_{ik}^{\downarrow}$ are the area fractions of the columns. Of course, the following requirements must be met:

$$\sum_{\ell=1}^{L} a_{i\ell}^{\uparrow} = 1 \quad ; \quad \sum_{k=1}^{K} a_{ik}^{\downarrow} = 1 \tag{7}$$

4. THE CLOUD SCENE RULES

For the construction of the cloud scene in the height/area-fraction scheme (Figure 1) we distinguish three cases (PANHANS, 1980a):

Isolated cloudy layers: In this case we assume that the overlapping of the clouds follows the rules of statistics:

$$P = \prod_{j=1}^{N} C_j \tag{8}$$

P beeing the overlap probability and C_j the cloud fractions of cloudy layers.

Clouds extending over continuous layers: In this case we assume that maximum overlap takes place.

Separated clouds, each extending over more than one layer: The situation is best explained by Figure 1. In this case two separated clouds are shown each of which extends through three sublayers. Cloudiness for each layer was calculated from the informations supplied by the circulation model.

The average cloud cover of the lower cloud is 0.5. The principle of maximum overlap is used here so that the cloud cover is started at area fraction 0.0. The average cloud cover of the upper cloud is 0.7. The two combined cloud layers with respect to each other are treated statistically so that the overlap is 0.35. This fixes the origin of the upper cloud at 0.15. Taking the origin 0.15 for the most upper cloud layer (no. 17) would, however, result in a total cloud cover exceeding 100 percent, so that a small correction is required. This simple scheme, of course, cannot handle in an exact manner all possible situations. Nevertheless, in this form the scheme is at least as satisfactory as the parameterization of the cloud cover from the circulation model.

If the cloud structure is very complicated, e.g. different cloud fractions from layer to layer, a very large number of small columns may result. Then the computing time would increase intolerably. To remove this difficulty, small displacements of the clouds and small changes of the cloud fractions are made so that the maximum number of columns is limited to e.g. 5 or 10 columns.

5. THE BLACK CLOUD APPROXIMATION

The column scheme works both for grey and black clouds but in the latter case it is not necessary to use this scheme. Integrations over cloudy layers are unnecessary, since the cloud droplet transmission function becomes zero, and the integral parts vanish.

Provided that the black-body assumption is correct, an instrument placed at the reference level registers only the visible parts of clouds which are not covered by clouds nearer to the reference level. In the example of Figure 1, the cloud in layer 11 is totally covered by the cloud in layer 10 and does not contribute to the downward flux at reference level i = 9. Furthermore, no cloud section from 0.0 to 0.5 above level 10 contributes to the downward flux at the reference level. Moreover, the water vapour ambiguity does not exist, because the integration is performed over cloud-free layers only. The consequence is that only one column must be regarded, but the vertical limits of this column may differ horizontally.

In order to treat this problem, we introduce so-called cloud scene factors $W_{in}^{\uparrow}$ and $W_{ij}^{\downarrow}$ instead of the column weights $a_{il}^{\uparrow}$ and $a_{ik}^{\downarrow}$. These cloud scene factors are the area fraction of the cloud in level $n(j)$ which contributes to the upward (or downward) flux in the reference level i, respectively (example on the right of Figure 1). The flux equations read then:

$$F_i^{\uparrow} = \sum_{n=1}^{i} W_{in}^{\uparrow} B(T_n) - $$
$$- \sum_{n=1}^{i} W_{in}^{\uparrow} \int_{T_i}^{T_n} \left[R^*(u(T)-u(T_i),T) + \Delta R^*(u(T)-u(T_i),u'(T)-u'(T_i),T)\right] dT \quad (9)$$

$$F_i^{\downarrow} = \sum_{j=i}^{N-1} W_{ij}^{\downarrow} B(T_j) + W_{iN}^{\downarrow} \int_{0}^{T_N} \left[R^*(u(T_i),T) + \Delta R^*(u(T_i),u'(T_i),T)\right] dT +$$
$$+ \sum_{j=i}^{N} W_{ij}^{\downarrow} \int_{T_j}^{T_i} \left[R^*(u(T_i)-u(T),T) + \Delta R^*(u(T_i)-u(T),u'(T_i)-u'(T),T)\right] dT \quad (10)$$

There is a considerable reduction of computing efforts compared with the grey model.

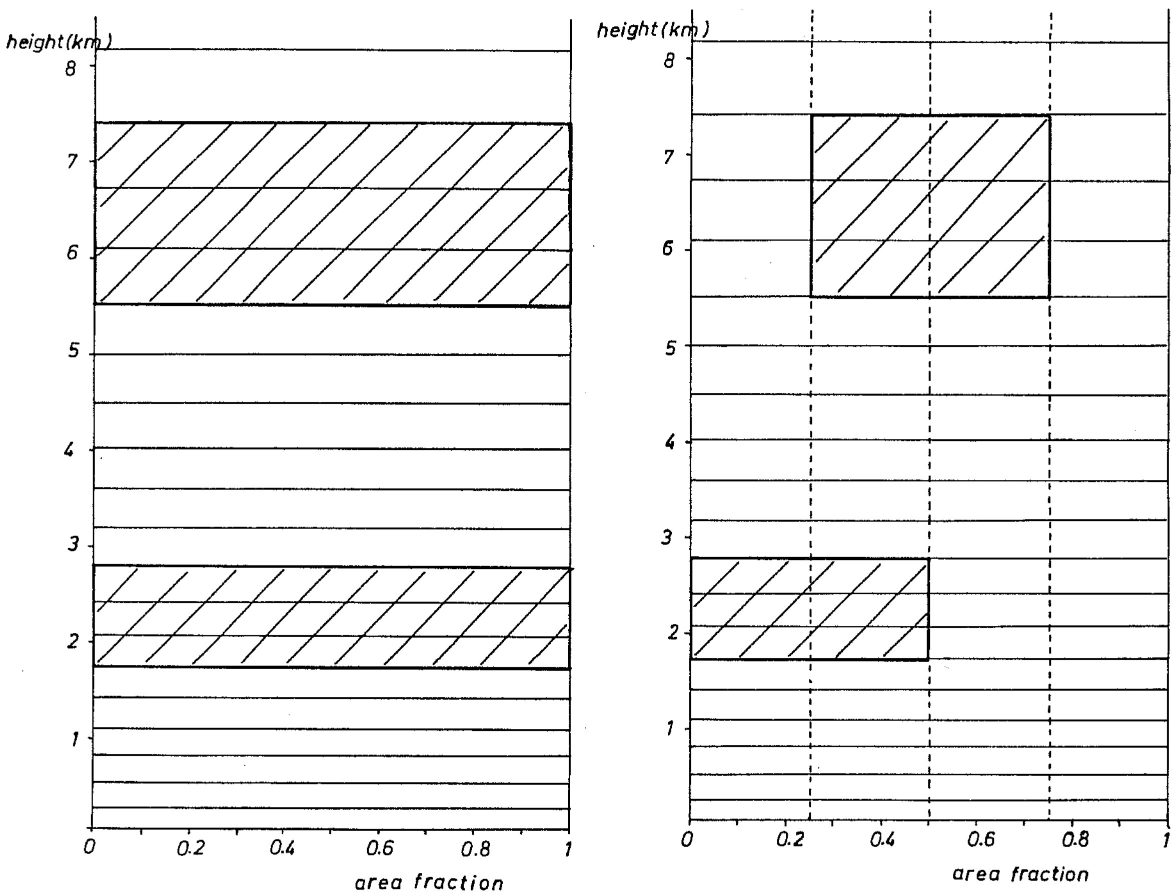
6. SELECTED RESULTS

For the first example a standard atmosphere has been chosen with two cloudy layers (1.7 - 2.8 km and 5.5 - 7.4 km). Figure 2 shows the vertical resolution and the column arrangement as seen from the earth's surface, with cloud fraction 1.0 (Figure 2a) and with cloud fraction 0.5 (Figure 2b).

Figure 3 shows radiative temperature changes for various situations. In the case of cloud fraction 1.0 strong cooling at the cloud tops and warming at the cloud bases are observed as expected. The differences in result between grey and black clouds are small in this example. In order to avoid discontinuities in the radiative temperature change distributions by setting the flux divergence equal to zero in the black cloud, a three-point formula is used. Assigning different mean temperatures for the cloud sections above and below the reference level also would result in non-zero flux divergences in the interior of the clouds. Only in case of isothermal black clouds the flux divergence would be zero.

For cloud fraction 0.5 the warming at the cloud bases is reduced, and so is the cooling at the top of the upper cloud . Nevertheless, at the top of the lower cloud the cooling is increased.

Looking for an explanation, we notice that at total cloud cover the loss of radiative energy at the top of the lower cloud is strongly



a) b)

Figure 2. Vertical resolution and column arrangement for a selected example as seen from the earth's surface. a) cloud fraction 1.0, b) cloud fraction 0.5

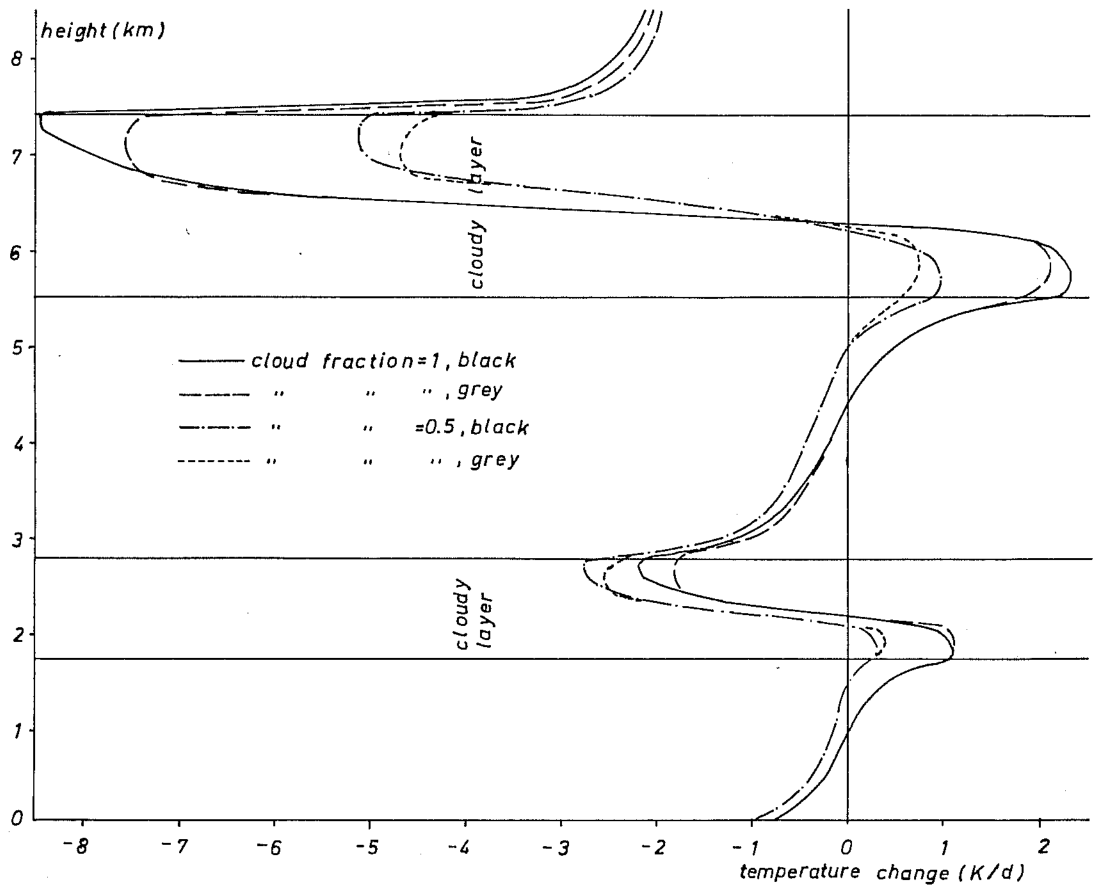


Figure 3. Radiative temperature changes for a standard atmosphere with the clouds of Figure 2.

compensated by the radiative energy emitted by the upper cloud. This is also true for 1 or 2 columns (depending on the reference level) at cloud fraction 0.5. But there is at least one column where only the lower cloud exists and not the upper one. In this column the upward emission of the lower cloud is not sufficiently compensated.

For the second example a winter atmosphere has been chosen with a temperature inversion between 100 and 1000 m (T (100) = 275 K , T (1000) = 283 K). The remainder of the atmosphere shows a standard temperature lapse rate. A cloud (or better: a fog) is fixed between 4 m and 100 m. The vertical resolution for calculations in the lower atmosphere was rather dense (4 - 10 m). In Table 1 again temperature changes due to long wave radiative divergences are presented for cloud fraction 1.0, black and grey, and cloud fraction 0.5, black and grey.

Table 1 Temperature changes due to long-wave radiative divergences for a winter atmosphere with a cloud between 4 and 100 m and a temperatur inversion between 100 and 1000 m

Height (m)	Temperatur change (K/day)			
	cloud fraction 1		cloud fraction 0.5	
	black	grey	black	grey
1000	-2.285	-2.276	-2.274	-2.269
700	-0.985	-0.974	-0.970	-0.964
400	-0.386	-0.364	-0.357	-0.346
200	0.099	0.197	0.204	0.253
100	-196.957	-50.855	-97.722	-24.671
80	0.	-31.593	0.372	-15.424
50	0.	-13.974	0.038	-6.949
20	0.	-5.710	-0.221	-3.076
12	0.	-5.110	-0.304	-2.859
4	0.691	-2.943	-0.127	-1.944

The most important result is that in both cases the very high cooling rates at the black cloud tops are reduced by about 75 percent for the grey clouds. Inside the black clouds the flux divergence vanishes due to the fact that the three point formula is used and that at each computational level the net flux is taken as zero. In the grey cloud continuously decreasing cooling rates with decreasing height are found. Note that for the black cloud the non-zero temperature changes at cloud fraction 0.5 result only from the cloud-free portion. Again, more realistic cooling rates are obtained from the grey scheme.

Table 2 Computing times (sec) on the Mainz Honeywell-Bull 66/80 computer

Example	grey	black
Winter atmosphere 36 layers cloud fraction 1.0	5.80	1.79
Winter atmosphere 36 layers cloud fraction 0.5 (2 columns)	9.28	2.54
standard atmosphere 28 layers, 2 clouds cloud fraction 1.0	3.87	1.31
standard atmosphere 28 layers, 2 clouds cloud fraction 0.5 (2-4 columns)	5.89	1.98

Table 2 shows the computing times for the above examples. The ECMWF Cray 1 computer is about 200 - 300 times faster than the Honeywell-Bull 66/80 machine at the University of Mainz.

8. CONCLUSIONS

The numerical experiments have shown that the black-body assumption for clouds is poor for models with a high vertical resolution. For such models (boundary layer models, urban-rural climate models, regional climate models etc.) it is necessary to use a continuous transmission function for cloud droplets. The assumption of grey absorption by clouds yields much more realistic radiative temperature changes.

Circulation models with low vertical resolution can treat clouds as black bodies using a three-point difference scheme. The critical layer thickness seems to be about 500 m. However, modern global and hemispheric models have a vertical grid distance of less than 500 m in the lower atmosphere. For such models, a long wave radiative scheme would be desirable, treating clouds grey in the lower atmosphere and black above where the resolution is lower, but it is not evident, whether it is possible to construct a combinded scheme which conserves the computational advantages of the black scheme described in Section 5.

Partial cloudiness is effective in any case and therefore should be accounted for in every circulation model.

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