On the shortwave radiative properties of stratiform water clouds

By A. SLINGO and H. M. SCHRECKER

Meteorological Office, Bracknell, England

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SUMMARY

The development of a comprehensive radiation scheme for computing shortwave fluxes and heating rates in a cloudy stratified atmosphere is described. The scheme uses the Delta-Eddington multiple scattering method and treats Rayleigh scattering, absorption by water vapour and ozone, and scattering and absorption by the cloud drops. The molecular absorption data were obtained from the Lowtran 3B subroutine and incorporated using the exponential sum fitting of transmissions technique. Five versions of the scheme were used to examine the effect of spectral resolution on the results and comparisons are shown with previous work. The short-wave properties of clouds were examined using 24 spectral bands between 0.25 and 4 µm. A significant dependence of the properties on the drop size distribution was found, in agreement with previous work. A simple parametrisation of the single scattering properties of the cloud drops in terms of liquid water content and equivalent radius was examined and shown to produce satisfactory results, thus circumventing the need for time-consuming Mie theory computations. This allows the scheme to be used in comparisons with aircraft measurements of layer clouds, within which both liquid water content and drop size distribution are functions of height.

1. INTRODUCTION

This paper describes the development of a solar radiation scheme, which is used in a study of the shortwave radiative properties of layer cloud. The work follows the similar development of an infra-red radiation scheme by Roach and Slingo (1979). Both schemes are designed for theoretical studies and for use in the analysis of experimental measurements of radiative fluxes within layer clouds. The infra-red scheme has been tested and employed to interpret data from a tethered balloon study of nocturnal stratocumulus (Roach et al. 1982, Caughey et al. 1982, Slingo et al. 1982a). Both schemes are also being used in the analysis of data from an aircraft study of daytime stratocumulus cloud over the sea, which were obtained during the JASIN experiment (Slingo et al. 1982b). An important application of this work is in the treatment of clouds in General Circulation Models. The fundamental role of clouds in the atmospheric energy balance is well recognised, and fully interactive models in which cloud amounts are predicted from the other model variables are now being used in climate studies (Herman et al. 1980, Wetherald and Manabe 1980). The detailed work on cloud radiative properties and their parametrisation is directly relevant, although a more basic problem remains the specification of cloud cover, type and distribution from the limited model variables (Slingo 1980).

The shortwave properties of clouds are dominated by the strong scattering by the cloud drops. The incident radiation is multiply scattered between the drops, increasing the optical path through the cloud, so that heating rates may be considerably larger than in clear air. The intense scattering reduces any anisotropy in the incoming radiation, creating a diffuse field which is more nearly isotropic. Under these conditions it is possible to derive equations for the fluxes in the upward and downward radiation streams, whilst direct radiation which remains unscattered may be treated as a delta-function with the appropriate intensity (Paltridge and Platt 1976, pp. 73–77). Such ‘two-stream’ approximations are very attractive as they are numerically fast and can therefore be included in larger numerical models. This speed is obtained at the expense of an error in the estimation of the net flux which typically may be only about one per cent (IAMAP 1977). Two-stream approximations have been presented by Kerschgens et al. (1978) and by Zdunkowski et al. (1980),
who also compared the performance of different versions. The Delta-Eddington approximation developed by Joseph et al. (1976) is the method which forms the basis of the scheme presented in this paper.

An important theoretical problem is the interaction between the multiple scattering and the absorption by water vapour in its various near infra-red spectral bands. Two methods have been devised for treating gaseous absorption in the presence of strong scattering. The first is the exponential-sum fitting of transmissions (ESFT) technique, by which the broad band transmissivity is approximated by a set of decaying exponentials (Wiscombe and Evans 1977). The great advantage of this method is that each of the exponents behaves like a monochromatic optical depth, which may be incorporated easily into a multiple scattering formalism. The alternative method of Photon Paths, favoured in the Russian work (e.g. Feigelson 1978), attempts to model more closely the fate of individual photons striking the cloud. A multiple scattering model is used to determine the probability distribution of photon paths through the cloud, the absorption then being calculated separately for each path. Despite the large apparent differences in approach and mathematical formulation, the two methods are essentially equivalent (Bakan et al. 1978).

The design of the radiation scheme and the data used are described in the next section. The scheme is then compared with previous work and the dependence of the results on the number of spectral bands used is determined. The sensitivity of the shortwave radiative properties of clouds to the drop size distribution is examined in detail. This leads to simple parametrizations of the single scattering properties of the cloud drops, enabling the scheme to calculate the shortwave properties of clouds with realistic vertical distributions of liquid water content and drop size distribution, without the need for further Mie theory computations.

2. DESCRIPTION OF RADIATION SCHEME

In planning the structure of a radiation scheme the wavelength dependence of the absorption and scattering must be taken into account. The upper curve in Fig. 1 shows the

![Figure 1](image_url)

Figure 1. The spectrum of direct solar radiation at the top of the atmosphere (upper curve) and at the ground (lower curve). The band limits for the five versions of the radiation scheme are also shown.
spectrum of the incident solar radiation at the top of the atmosphere, as determined by Thekaekara and Drummond (1971). The lower curve represents the spectrum of direct radiation at the ground for a mid-latitude winter atmospheric profile, 60° solar zenith angle and no clouds. This curve was calculated using the Lowtran 3B subroutine (Selby et al. 1976), which is an invaluable summary of a large quantity of gaseous absorption line information, and has become a standard source of such data. It allows atmospheric transmission to be calculated for any cloud-free path, for wavenumber intervals of 5 cm⁻¹ from 350 to 40,000 cm⁻¹ (28.5–0.25 μm). The shaded area between the two curves represents radiation which has been absorbed or scattered. The important features are the strong absorption by ozone at wavelengths shorter than 0.3 μm, the depletion due to Rayleigh scattering up to about 0.7 μm, the oxygen absorption feature at 0.76 μm and the strong water vapour absorption around 0.94, 1.12, 1.38, 1.87, 2.7 and 3.2 μm. In the present scheme gaseous absorption by water vapour and ozone are treated. Oxygen and carbon dioxide have a very small effect on tropospheric fluxes and heating rates (Liou et al. 1978) and have therefore been ignored.

The shortwave fluxes and heating rates in a cloudy atmosphere are profoundly influenced by multiple scattering from the cloud drops. Absorption by the drops also takes place in the same regions of the near infra-red spectrum as that by water vapour. The resulting combined extinction has a strong wavelength dependence so that radiation schemes need several spectral bands to treat the change in shape of the incident spectrum as it interacts with a cloud. In this study, five versions of the radiation scheme with very different spectral resolutions are therefore used to examine the number of bands necessary for these calculations. The band limits chosen are listed in Table 1 and illustrated in Fig. 1. The simplest version uses only one spectral band, whilst the most detailed has 24 bands distributed so as to resolve the major spectral features shown in Fig. 1. Only one gas can be

**TABLE 1. DETAILS OF THE BAND STRUCTURE OF EACH VERSION OF THE RADIATION SCHEME. THE BAND LIMITS ARE IN WAVE NUMBERS (cm⁻¹). THE SYMBOLS INDICATE THE TREATMENT OF ABSORPTION BY WATER VAPOUR (*) AND OZONE (+) AND AN ATMOSPHERIC WINDOW (W)**

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treated in a given band and for this reason water vapour is modelled in the single band scheme but not ozone.

Within each spectral band the interaction between multiple scattering and absorption needs to be modelled in order to calculate the radiative fluxes at each vertical level. The present scheme uses the Delta-Eddington technique (Joseph et al. 1976), extended by Wiscombe (1977) in the form of a Fortran subroutine. This is a fast and accurate ‘two-stream’ method which has been used in studies of the radiative properties of Saharan dust (Carlson and Benjamin 1980) and may also be incorporated into climate models (Leighton 1980). The incident solar flux at 100 km altitude is assumed to follow the extraterrestrial spectrum of Thekaekara and Drummond (1971). The Lowtran 3B subroutine is used at a resolution of 20 cm\(^{-1}\) to find the atmospheric transmission down to about 10 km and hence define the incident flux in each band at this level. The Delta-Eddington scheme is then used with typically 40 unequally spaced levels between 10 km and the surface, with 10–15 cloudy levels. Direct and diffuse downward fluxes and the upward diffuse flux are computed by the scheme for each model level. These fluxes are summed across the bands to give the integrated shortwave fluxes, the heating rates being given by the divergence of the net downward flux.

The input data to the Delta-Eddington method are the solar zenith angle and the incoming solar flux for the band, the surface albedo and the single scattering parameters for each level. These parameters are the optical depth \(\tau\), the single scattering albedo \(\omega\) (which gives the fraction of \(\tau\) accounted for by scattering, as opposed to by absorption) and the asymmetry factor \(g\) (which gives the asymmetry of the scatter between the forward and backward hemispheres). For an explanation of the methodology of two-stream approximations see Paltridge and Platt (1976), chapter 4. It is possible to take into account the effects of gaseous absorption \(G\), Rayleigh scattering \(R\) and extinction by the cloud drops \(D\) by summing the single scattering parameters for each process in the following way (see e.g. Liou et al. 1978);

\[
\tau = \tau_G + \tau_R + \tau_D \quad \cdots \quad \cdots \quad \cdots \quad (1)
\]

\[
\omega = (\tau_R + \omega_D \tau_D) / \tau \quad \cdots \quad \cdots \quad \cdots \quad (2)
\]

\[
g = g_D \omega_D \tau_D / \omega \tau \quad \cdots \quad \cdots \quad \cdots \quad (3)
\]

The methods used to calculate the terms in these equations will now be discussed.

(a) Gaseous absorption

The effect of gaseous absorption on the fluxes in each band is determined by the dependence of the transmissivity \(T(u)\) on absorber amount \(u\). Lowtran 3B was used to compute the transmissivity along a horizontal path at standard temperature and pressure, at a wavenumber resolution of 5 cm\(^{-1}\) across each band. The individual transmissivities were then weighted with the solar spectrum of Thekaekara and Drummond (1971), which was interpolated to this resolution, and summed to derive the mean transmissivity of the band. This is obviously an approximation as the spectrum changes through the atmosphere, but the approximation improves as the number of bands is increased because spectral changes are then treated more exactly. This procedure was repeated for 30 values of absorber amount to build up the transmissivity curve, the values being spaced logarithmically to preserve accuracy at small absorber amounts. The values used ranged from 0·006 to 10 g cm\(^{-2}\) for water vapour and 3 \times 10^{-7} to 10^{-2} g cm\(^{-2}\) for ozone.

The solid curve on Fig. 2 shows an example of the resulting absorptivity (1 – \(T(u)\)) for water vapour across the entire solar spectrum (0·25 to 4 \(\mu\)m). The dashed line is the absorptivity calculated as above but using the solar spectrum tabulated in the Handbook of Geophysics (1960). This spectrum has proportionally less flux beyond 1 \(\mu\)m than that of Thekaekara and Drummond (1971) with the result that the broad band absorption is always smaller. This illustrates the fact that absorptivities are as much influenced by the choice of spectral weighting as by the basic absorption data. Fouquart and Bonnel (1980) used Lowtran 3B and the Handbook of Geophysics spectrum in their radiation scheme and the absorptivity curve shown here is identical to that in their paper. The dashed-dotted
Figure 2. Water vapour absorptivity across the entire solar spectrum as a function of absorber amount for two solar spectra and for the work of Lacis and Hansen (1974).

curve was derived by Lacis and Hansen (1974) and is of similar shape to the other two, except that it predicts significantly larger absorption at large absorber amounts. This is primarily due to the different absorption data used by those authors.

The gaseous absorption data were incorporated into the radiation scheme by fitting the transmissivity curves using the ESFT technique referred to in the introduction. The equation

$$T(u) = \sum_{i=1}^{N} a_i \exp(-b_i u).$$

(4)

has to be inverted to find the coefficients $a_i$ and $b_i$ for $i = 1, N$. By fitting the curves in this way each of the exponents may be identified as an optical depth and therefore can be used directly in Eq. (1). A computer program to solve Eq. (4) for unevenly-spaced $u$, using the algorithms of Cantor and Evans (1970), was kindly made available to the authors by Dr J. F. Geleyn (personal communication). The number of terms required, $N$, depends on the complexity of the absorption. For some ozone bands only three terms were needed, whereas up to twelve were used to fit the water vapour bands. The root-mean-square error in the fits was in all cases <0.01% or less, which is smaller than the thickness of the lines on Fig. 2. The algorithms ensure that the sum of the $a_i$ is unity, so that flux is conserved, and that the $b_i$ are always real and positive. All the molecular data are summarized by these coefficients which are stored in the radiation scheme. For bands in which there is no gaseous absorption $T(u)$ is unity and hence $i = 1$, $a_1 = 1$ and $b_1 = 0$.

The pressure and temperature dependence of the water vapour absorption are taken into account using the Lowtran 3B scaling. A scaled absorber amount $u'$ is defined, taking into account the pressure $p$, temperature $T$ and absorber amount $u$ in each vertical layer;

$$u' = u\left(\sqrt{\frac{T_0}{T}}\right)^{p/p_0}$$

(5)

where $p_0 = 1013$ mb and $T_0 = 273.15$ K. No scaling is used for the ozone absorber amounts. Although the use of pressure and temperature scaling is common in such approximate...
methods, it does not appear to have been validated in conditions of multiple scattering. Comparisons with more exact methods are needed to assess the accuracy of such scaling.

The ESFT technique effectively results in a division of each spectral band into \( N \) sub-bands. In each of these sub-bands \( i \) the layer optical depth for gaseous absorption, \( \tau_{\text{g},i} \), is given by:

\[
\tau_{\text{g},i} = b_{\text{g}} u'_i \quad \quad \quad \quad \quad \quad (6)
\]

For gaseous absorption the single scattering albedo and asymmetry factor are both zero and so do not appear in Eqs. (2–3). Within each spectral band the Delta-Eddington subroutine is therefore called \( N \) times, the only change being substitution of the \( \tau_{\text{g},i} \) terms from Eq. (6) into Eq. (1). The incident fluxes used in each call are the fraction \( a_i \) of the incident flux in that band. In the 24-band version of the radiation scheme the subroutine is called 141 times, which is why it is essential that the multiple scattering technique should not only be accurate but numerically fast. Absorption by more than one gas in each band cannot be treated by this method, as the \( a_i \) would undoubtedly be different, but in practice this does not matter as the principal absorbers (water vapour and ozone) occupy different regions of the spectrum.

\( b) \) Rayleigh scattering

Rayleigh scattering is included for all layers and in all spectral bands. Penndorf’s (1957) formulation of the volume extinction coefficient \( \beta_R \), which has been used in most studies, can be written:

\[
\beta_R = 0.9793 (n_e^2 - 1)^2 p/\lambda^4 T 
\]

where air pressure \( p \) and temperature \( T \) are in mb and K, respectively, and wavelength \( \lambda \) is in microns. Edlén’s (1953) formula for the refractive index of air, \( n_e \), is used. More recent work by Hoyt (1977) suggests that \( \beta_R \) should be 3\% to 4\% lower than Penndorf’s values, but this makes a very small difference to the present work. The strong wavelength dependence of both \( \beta_R \) and the solar irradiance \( P_\lambda \) may be taken into account by defining for each band the constant \( R \):

\[
R = 0.9793 \int (n_e^2 - 1)^2 P_\lambda \lambda^{-4} d\lambda / \int P_\lambda d\lambda 
\]

These constants were calculated in a separate program using high spectral resolution in the evaluation of the integrals. The Rayleigh optical depth \( \tau_R \) of a layer of geometric thickness \( \Delta z \) (in metres) is then:

\[
\tau_R = R p \Delta z / T 
\]

Rayleigh scattering involves no absorption of the incident radiation and the scattered field is symmetric, so the single scattering albedo is unity and the asymmetry factor zero.

\( c) \) Extinction by the cloud drops

The single scattering properties of the cloud drops are required by Eqs. (1–3) for all levels and bands. These properties may be calculated using Mie theory (van de Hulst 1957), making the usual assumption that the cloud is composed of spherical drops of pure water. Mie theory calculations can be expensive and simple parametrizations are therefore derived in Section 5 to obtain these properties directly from the liquid water content and drop size distribution. It is conventional to calculate the volume extinction coefficient \( \beta_v \), from which the optical depth \( \tau_v \) due to drops in a homogeneous layer is given by:

\[
\tau_v = \beta_v p \Delta z 
\]

The values of \( \tau_v, \omega_3 \) and \( \omega_6 \) are strictly averages over each spectral band, weighted by the incident flux as in Eq. (8), but it is common practice to use values calculated for the central wavelengths alone (e.g. Liou et al. 1978).

3. Comparisons with other schemes

In comparing the results from this scheme with previous work it must be remembered that disagreements between radiation schemes are often as much due to differences in the
choice of absorption, scattering and spectral data as to deficiencies in the various approximations used. The five versions of the present scheme differ only in the number of spectral bands and therefore allow the error from this source to be examined in detail. This is an important consideration as the computing time required is directly proportional to the number of bands.

As part of the development of their parametrization scheme, Lacis and Hansen (1974) presented single spectral band calculations of absorption by water vapour in a cloudless atmosphere with no Rayleigh scattering. The present single band scheme has been run using their ESFT coefficients and temperature and pressure scaling. The heating rate profile is shown in Fig. 3 and is indistinguishable from the curve presented by Lacis and Hansen (their Fig. 12). This illustrates that the Delta-Eddington code, developed to deal with multiple scattering in clouds, can also treat satisfactorily the much simpler case of gaseous absorption in an atmosphere with no scattering. Also shown on Fig. 3 are the heating rates for the other two absorptivity curves from Fig. 2, using the Lowtran 3B scaling as described in the previous section. In general the heating rates agree very well, but the differences which do occur can be related to the differences in the absorptivity curves. The Lacis and Hansen absorptivity, for example, is much lower than the other two at low absorber amounts but crosses the Thekaekara and Drummond curve just beyond 1.48 g cm$^{-2}$, which is the effective total absorber amount for this profile. The heating rate is therefore lower in the upper troposphere, with a corresponding increase near the ground. The Handbook of Geophysics absorptivity is always lower than that for the Thekaekara...
and Drummond solar spectrum and this results in systematically lower heating rates. The heating rate profiles for all five versions of the scheme, using the Lowtran 3B data and scaling and the Thekaekara and Drummond spectrum, are shown in Fig. 4. The differences between the profiles are small and illustrate that for such a simple test a single spectral band model performs well. The small systematic differences are due to the fact that only the higher spectral resolution versions can treat the changes in shape of the infra-red spectrum as the solar flux is absorbed.

![Graph showing heating rate profiles](image)

**Figure 4.** As for Fig. 3 but for all 5 versions of the scheme.

Braslau and Dave (1973) performed computations for several cloudless atmospheres using an 83-band radiation scheme, which included explicit calculations of the intensity as a function of zenith angle. The comparisons shown in Table 2 are for an atmosphere with Rayleigh scattering and absorption by water vapour and ozone. Absorption by oxygen and carbon dioxide were also included by Braslau and Dave, although the contribution from these gases is very small. The entries in the table give the percentages of the incident solar flux at 45 km altitude which is directly or diffusely transmitted through, reflected from and absorbed by the atmosphere for four combinations of solar zenith angle and surface albedo. In comparing the five versions of the present scheme with each other it will be seen that, as in the previous comparisons, good results are obtained with only a few spectral bands, although systematic changes do occur as the number of bands is increased. The single band scheme ignores ozone absorption, which leads to a systematic underestimate of the atmospheric absorption, especially at large zenith angles. In all cases the contribution by
TABLE 2. COMPARISON WITH BRASLAU AND DAVE (1973)

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<th>Solar zenith angle/surface albedo</th>
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<th>Diffusely transmitted</th>
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<tr>
<td>67.81</td>
<td>8.98</td>
<td>76.78</td>
<td>28.81</td>
<td>17.44</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>69.29</td>
<td>8.35</td>
<td>77.64</td>
<td>28.57</td>
<td>17.08</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>69.31</td>
<td>8.34</td>
<td>77.64</td>
<td>28.57</td>
<td>17.08</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>70.06</td>
<td>8.80</td>
<td>78.86</td>
<td>27.99</td>
<td>16.76</td>
<td>B/D</td>
<td></td>
</tr>
<tr>
<td>40.65</td>
<td>25.62</td>
<td>66.28</td>
<td>71.53</td>
<td>15.21</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>40.40</td>
<td>23.86</td>
<td>64.26</td>
<td>66.84</td>
<td>20.31</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>50.77</td>
<td>16.75</td>
<td>67.51</td>
<td>64.92</td>
<td>21.58</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>52.28</td>
<td>16.26</td>
<td>68.54</td>
<td>64.34</td>
<td>20.95</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>52.38</td>
<td>16.20</td>
<td>68.58</td>
<td>65.33</td>
<td>20.96</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>51.29</td>
<td>16.65</td>
<td>67.94</td>
<td>62.64</td>
<td>23.75</td>
<td>B/D</td>
<td></td>
</tr>
</tbody>
</table>

Ozone to the total atmospheric absorption is, however, much smaller than that by water vapour. The fluxes from the 15- and 24-band versions are almost identical. The 24-band scheme gives fluxes which are generally within 2% of those calculated by Braslau and Dave (1973). The differences are primarily due to the different absorption data used, although the larger disagreement at 80° zenith angle is possibly due to the deterioration in accuracy of the Delta-Eddington approximation which is known to occur at large zenith angles (Joseph et al. 1976).

In the final example, heating rates within a cloud layer are calculated. The cloud is 500 m thick, with its base at 1 km, with a Stratocumulus II drop size distribution and a uniform liquid water content of 0.47 g m⁻³, in a tropical atmosphere at 0° solar zenith angle above a surface with albedo 0.3 (data from Stephens 1978a). Absorption by water vapour and extinction by cloud drops are included. The present schemes also incorporate Rayleigh scattering, although this has a very small effect on the fluxes and heating rates in cloud. The single scattering properties of several drop size distributions, including Stratocumulus II, were calculated from Mie theory and tabulated as a function of wavelength by Stephens (1979). These were interpolated and weighted with the Thekaekara and Drummond solar irradiance $P_\lambda$ to obtain average values in each spectral band;

\[
\beta_B = \int \int \beta_\lambda P_\lambda d\lambda \int P_\lambda d\lambda
\]

\[
\omega_B = \int \omega_\lambda \beta_\lambda P_\lambda d\lambda \int \beta_\lambda P_\lambda d\lambda
\]

\[
\varepsilon_B = \int \varepsilon_\lambda \omega_\lambda \beta_\lambda P_\lambda d\lambda \int \omega_\lambda \beta_\lambda P_\lambda d\lambda
\]

\[
(11)
\]
where the limits of the integrals are the edges of the spectral band.

These equations provide good estimates of the single scattering properties, provided that the band is not too broad. Droplet absorption takes place in a few strong near infra-red bands, which overlap those of water vapour. There is therefore a limit to the fraction of the solar beam which can be absorbed, amounting to about 20% for a deep cloud layer. Application of these equations to a wide spectral band artificially creates the possibility of absorption over a much larger fraction of the solar spectrum. As the number of spectral bands used in the scheme is reduced this can lead to a progressive overestimate of the true absorption. This is illustrated in Fig. 5, in which the solid lines are the heating rate profiles for each version of the radiation scheme. The 15- and 9-band versions have identical band structure in the infra-red and hence have identical heating rates. Except at cloud top, these agree closely with the 24-band values. The 3-band scheme overestimates the heating rates and the single-band version produces unrealistically large values. The heating rates from this version are so large that only the lower portion of the profile can be shown on Fig. 5. In other tests the disagreement between the higher spectral resolution versions has been more marked. These results suggest that at least one band is needed to treat each of the major water vapour absorption features in the near infra-red. For the rest of this paper the 24-band version will therefore be used. Despite the large number of bands, the computing time required for such a profile is only a few seconds on an IBM 360/195 computer.

The heating rate profile calculated by Stephens (1978a) for this cloud is shown as the dotted line on Fig. 5. This is very similar in shape to the 24-band profile, although the total cloud absorption is about 25% higher. The disagreement cannot be due to the resolution problem discussed above as Stephens (1978a) used 15 spectral bands in a very similar configuration to the 15-band version of the present scheme. There are several differences between the schemes, however, such as the multiple scattering techniques used and the gaseous absorption data, which could contribute to the disagreement. This emphasizes the need for more comparisons between radiation schemes for standard cloudy atmospheres, so as to examine more closely the factors which lead to such disagreements.

![Figure 5. Comparison of the heating rate profiles in a cloud layer for all 5 versions of the scheme with the work of Stephens (1978a).](image)
4. Dependence on the Drop Size Distribution

Twomey (1976) examined the dependence of cloud shortwave properties on the drop size distribution, and showed that as the mean drop radius is increased at constant liquid water content there is a small increase in the absorption and a larger increase in the transmission of the cloud. These effects reinforce because an increase in transmission leads to a greater absorption by the surface. Clouds growing in a 'clean' maritime airmass tend to have larger drops than continental clouds of the same liquid water content and this therefore leads to a significantly larger absorption by the cloud-surface system. Stephens (1978a), Liu and Wittman (1979) and Welch et al. (1980) obtained similar results, although Stephens found little variation in the cloud absorption.

In the above studies the temperature and water vapour profiles were taken from standard atmospheres. Clouds were introduced with liquid water contents obtained from the few aircraft measurements available and the water vapour densities inside cloud were increased to their saturation values. Boundary layer cloud has now been studied in some detail, however, and this approach is no longer necessary. Recent observational studies of the stratocumulus-capped boundary layer have shown that such cloud is surmounted by a strong, relatively dry inversion and that the temperature profile is close to adiabatic in the cloud and sub-cloud layers and hence different from that in standard atmospheres (Wakefield and Schubert 1976, Roach et al. 1982). The humidity mixing ratio is nearly

![Dew Point Depressions Diagram](image)

**Figure 6.** Tephigrams for the three atmospheric profiles used in section 4.
TABLE 3. DETAILS OF THE ADIABATIC CLOUDS INSERTED INTO THE PROFILES ILLUSTRATED IN FIGURE 6

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Arctic</th>
<th>Mid-latitude</th>
<th>Subtropical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud Base Pressure (mb)</td>
<td>1000.0</td>
<td>961.5</td>
<td>930.0</td>
</tr>
<tr>
<td>Cloud Base Temperature (K)</td>
<td>270.2</td>
<td>278.6</td>
<td>292.2</td>
</tr>
<tr>
<td>Cloud Top Pressure (mb)</td>
<td>964.0</td>
<td>915.1</td>
<td>880.0</td>
</tr>
<tr>
<td>Cloud Top Liquid Water Content (g m⁻³)</td>
<td>0.4107</td>
<td>0.7353</td>
<td>1.110</td>
</tr>
<tr>
<td>Liquid Water Path (g m⁻³)</td>
<td>60.6</td>
<td>151.4</td>
<td>268.6</td>
</tr>
</tbody>
</table>

constant in the sub-cloud layer, showing that it is well mixed. The liquid water content of the cloud is close to the adiabatic profile, which is calculated by assuming adiabatic ascent of saturated air from cloud base.

In this section the dependence of cloud shortwave properties on drop size distribution will be examined for boundary layer clouds in three atmospheres with realistic temperature and humidity structure. Details of the profiles are given in Fig. 6 and Table 3. The subtropical profile is taken from the 23 GMT radiosonde ascent from Sal, Cape Verde Islands, on 8 September 1974 during GATE, when 6/8 stratocumulus was reported. The mid-latitude profile was obtained on 8 August 1978 during the Joint Air-Sea Interaction experiment (Pollard 1978), in which detailed radiation and cloud physics measurements were made from research aircraft in a study of marine stratocumulus. The arctic profile is based on the 12 GMT radiosonde ascent from Barrow, Alaska, on 13 July 1963, when 8/8 stratus was reported. The cloud is assumed to be homogeneous, although arctic stratus is often observed to be multi-layered (Herman 1977). The only change made to these profiles has been to constrain the temperatures to follow the adiabatic profiles exactly in and below cloud and to assume a constant humidity mixing ratio below cloud base. The deviations of the original data from these idealized profiles in this region are small.

Details of the eight drop size distributions used are given in Table 4. These are taken

TABLE 4. THE EIGHT DROP SIZE DISTRIBUTIONS USED IN THIS STUDY

<table>
<thead>
<tr>
<th>Drop Size Distribution</th>
<th>Liquid Water Content (g m⁻³)</th>
<th>Mode Radius (μm)</th>
<th>Equivalent Radius (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>St 2</td>
<td>0.05</td>
<td>2.25</td>
<td>4.21</td>
</tr>
<tr>
<td>Sc 1</td>
<td>0.14</td>
<td>3.5</td>
<td>5.40</td>
</tr>
<tr>
<td>St 1</td>
<td>0.22</td>
<td>3.5</td>
<td>5.93</td>
</tr>
<tr>
<td>As</td>
<td>0.28</td>
<td>4.5</td>
<td>6.20</td>
</tr>
<tr>
<td>Ns</td>
<td>0.50</td>
<td>3.5</td>
<td>9.33</td>
</tr>
<tr>
<td>Sc 2</td>
<td>0.47</td>
<td>7.5</td>
<td>9.91</td>
</tr>
<tr>
<td>Cu</td>
<td>1.00</td>
<td>5.5</td>
<td>12.19</td>
</tr>
<tr>
<td>Analytic</td>
<td>1.21</td>
<td>15.5</td>
<td>16.6</td>
</tr>
</tbody>
</table>

from the tabulations of Stephens (1979) but omit the Cb distribution as it contains too many large drops for the present purpose. It is replaced by an analytic distribution defined by the modified gamma function;

\[ n(r) = 10^{-17} r^{2.0} \exp(-0.22 r^{1.5}) \]  \hspace{1cm} (12)

where \( n(r) \) is the drop size distribution function and the radius \( r \) is measured in microns. The extinction properties of the distribution were calculated from Mie theory for a range of wavelengths from 0.25 to 4 μm, using the complex refractive index data from Hale and Querry (1973), as used by Stephens (1979). The average single scattering properties of each distribution in each of the 24 spectral bands were then calculated using Eq. (11), as described in the previous section. The liquid water contents listed in Table 4 are not used here. The Cumulus data are included merely to exercise the scheme over as wide a range of distri-
butions as possible, and it must be remembered that the layer cloud approximation may no longer be valid in broken cloud conditions.

The final column in Table 4 lists the equivalent radius of each distribution;

$$r_e = \int_0^\infty n(r) r^3 dr / \int_0^\infty n(r) r^2 dr.$$  \hspace{1cm} \hspace{1cm} (13)

This is an extremely useful moment of the distribution because for drops of the sizes typically found in clouds it is possible to estimate the short-wave volume extinction coefficient $\beta_D$ (and hence the optical depth of the cloud) directly from the liquid water content (LWC) and equivalent radius (Paltridge and Platt 1976, page 80);

$$\beta_D \approx 3 \text{ LWC} / 2r_e.$$  \hspace{1cm} \hspace{1cm} (14)

This expression gives $\beta_D$ in m$^{-1}$ when the liquid water content is in g m$^{-3}$ and the equivalent radius is in $\mu$m.

The liquid water content at each level within the cloud was assumed to follow the adiabatic profile and the volume extinction coefficients were scaled accordingly. The relative amounts of water vapour and liquid water were therefore fixed in a realistic way. In order to examine the importance of water droplet absorption, two parallel runs of the radiation scheme were made in each case. In the first the single scattering properties were used as described above, but in the second droplet absorption was suppressed by fixing the single scattering albedos at unity. The volume extinction coefficients were adjusted so that the scattering extinction coefficients were unchanged, which ensures that the only difference between the two runs is the removal of droplet absorption. Two runs were made for each profile and each drop size distribution, using a solar zenith angle of 60° and surface albedo of 0·07.

The values of cloud absorption and the albedo of the cloud-surface system are plotted on Fig. 7 as a function of the equivalent radius of the distribution. The albedos and absorptions are expressed as percentages of the total downward flux at cloud top. The solid curves were drawn by eye through the points for the runs with absorption by both water vapour and liquid water. The vertical displacement of the curves reflects the different water vapour and liquid water paths through the clouds. Liou and Wittman (1979) show that the absorption and albedo are strong functions of the cloud liquid water path and solar zenith angle. With this in mind, Fig. 7 should be seen as an example of the additional dependence on drop size distribution which may be expected. These clouds are relatively thin so that the absorptions are much smaller than the maximum value of about 20% for a very thick cloud. Figure 7 shows that the effect of increasing the equivalent radius is to reduce the system albedo and to increase the cloud absorption slightly, as was also found by Twomey (1976). A reduction in albedo was also found by Stephens (1978a), Liou and Wittman (1979) and Welch et al. (1980), who also all found the absorption dependence to be weak. The reduction in system albedo is a result of an increase in the transmission through the cloud, which is caused by a decrease in the cloud optical depth as given by Eq. (14). The absorption efficiency of water drops increases rapidly with radius, however, so that the cloud absorption increases despite the decreasing optical depth. In the transition from continental to maritime clouds $r_e$ may be expected to range between about 5 and 15 $\mu$m.

As Fig. 7 shows, this results in a significant change in the cloud shortwave properties.

Also shown in Fig. 7 are the cloud absorptions for the runs in which droplet absorption was suppressed. The absorptions for the arctic profile are not shown as they are too close to the values for the mid-latitude cloud. These values are far smaller than the previous absorptions and show clearly that for such boundary layer clouds it is the drops themselves which are responsible for the bulk of the absorption and that water vapour makes a minor contribution. This is in agreement with the results of Welch et al. (1980, p.9), although Stephens (1978a) finds water vapour to be more important than this. The different conclusions are primarily due to the different relative amounts of water vapour and liquid water used, which illustrates the point made earlier that in such sensitivity studies
Figure 7. Cloud absorption and system albedo for the three atmospheric profiles shown in Fig. 6 as a function of the equivalent radius of the drop size distribution. The clear sky absorptions are shown by the horizontal bars.

these should be chosen carefully according to the meteorological context. The system albedo for these cases is increased by only a few per cent and for clarity the values are therefore not shown on the figure. It is interesting to note that the very low absorptions for these runs are smaller than the clear sky values for the same profiles but with no cloud, shown as the horizontal bars on Fig. 7. This is because the introduction of a cloud with only droplet scattering results in a large proportion of the solar beam being reflected back to space from cloud top. The increase in the water vapour path due to the strong multiple scattering within the cloud may not be sufficient to counteract the loss of such a large fraction of the solar beam, so that the heating rates can be reduced. In contrast, Lacis and Hansen (1974) show similar calculations for which the water vapour absorption is relatively stronger, so that the total cloud absorption is slightly greater than in the clear sky case.
5. Parametrization of Mie single scattering data

The albedos and absorptions illustrated in Fig. 7 show an almost monotonic dependence on the equivalent radius of the drop size distribution, despite the fact that three of the distributions used have identical mode radii (Table 4). This suggests that details of the shape of the drop size distribution may be unimportant in determining the shortwave radiative properties of clouds. Before exploring a possible parametrization, however, it is instructive to look in detail at the dependence of the single scattering properties on wavelength. Figure 8 shows the single scattering properties as a function of wavelength for three of the

Figure 8. The single scattering properties of three drop size distributions as a function of wavelength.
drop size distributions introduced in the previous section, using the liquid water contents listed in Table 4.

The volume extinction coefficients show only a weak dependence on wavelength, except in the vicinity of the strong absorption band at about 3 μm. The horizontal bars to the left of the figure show the values of the volume extinction coefficient given by Eq. (14). This equation is valid if the drops are very much larger than the wavelength, so one should expect closest agreement with the Mie calculations at the shorter wavelengths. This is certainly the case for the large drops of the analytic distribution, although there are systematic differences for the smaller drops of the Stratocumulus II and especially the Stratus distributions. Nevertheless, the parametric form of Eq. (14) describes the dependence of the volume extinction coefficient on the liquid water content and drop size distribution fairly well.

The plots of single scattering albedo can be thought of as showing the absorption spectrum of water drops. At wavelengths shorter than about 1 μm absorption is negligible, whereas beyond 1 μm there are several distinct absorption bands, which correspond roughly to the bands of water vapour in this region. It is important to note that the albedo shows a systematic dependence on drop size distribution, the albedo being in general smallest, and hence the absorption greatest, for the large drops of the analytic distribution. This dependence is reversed in the centre of the 3 μm band. The asymmetry factor shows little variation with either wavelength or drop size distribution, which is why an average value of 0.85 has often been taken in the literature. The small dependence on drop size distribution is systematic, however, except at the edges of the 3 μm absorption band. Cloud radiative properties depend only weakly on the asymmetry factor, so this is a relatively unimportant parameter (see later).

These results suggest that a parametrization of \( \beta_D, \omega_D \) and \( g_D \) in terms of liquid water content and effective radius is worth investigating. Such a parametrization would provide a means of calculating the single scattering properties without the need for Mie theory calculations. The theoretical studies of cloud radiative properties published so far have all assumed a single drop size distribution, whereas observations show that, at least in the case of stratocumulus, the drop size distribution varies with height within the cloud (e.g. Slingo et al. 1982a, b). To take account of this variation by calculating the single scattering properties from Mie theory for each level and each spectral band would be prohibitively expensive.

The mean single scattering properties of the eight drop size distributions in each spectral band were fitted using the following simple functions;

\[
\beta_D = LWC(a + b/r_e) \quad . \quad . \quad . \quad (15)
\]

\[
1 - \omega_D = c + d r_e \quad . \quad . \quad . \quad (16)
\]

\[
g_D = e + f r_e \quad . \quad . \quad . \quad (17)
\]

The coefficients \( a, b, c, d, e \) and \( f \) were obtained by performing least squares fits of these functions to the data. It was found that these equations provide a good representation of the single scattering properties. As an example, Fig. 9 shows the fits obtained for band number 22, which covers the wavelength range 2.38 to 2.91 μm, where the single scattering properties show a strong dependence on wavelength. A good fit to the dependence of the volume extinction coefficient on equivalent radius was obtained, as would be expected from Eq. (14). The most important result is the goodness of fit to \( 1 - \omega_D \) obtained by the simple linear dependence on \( r_e \) used in Eq. (16). Cloud absorption is extremely sensitive to \( 1 - \omega_D \) and a good fit in the bands where droplet absorption is high is central to the usefulness of the parametrization. Such a linear dependence of \( 1 - \omega_D \) on radius has also been noted recently by Twomey and Bohren (1980). The asymmetry factor shows little variation between drop size distributions in this band and the weak dependence on equivalent radius is adequately represented by Eq. (17).

Two examples of the use of these parametrizations are presented in Fig. 10. The
computations use the mid-latitude clouds introduced in section 4 with the Stratus II and Analytic drop size distributions. The solid lines show the heating rate profiles calculated as described in section 4. The overall cloud absorptions and albedos are listed in the inset tables for these 'exact' calculations. The profiles are more strongly peaked towards cloud top than the example shown in Fig. 5 because of the increase of liquid water content with height. It is also interesting to note that the profiles shown on Fig. 10 are not of the same shape. The larger optical depth of the Stratus II distribution results in more intense multiple scattering, which gives rise to the higher system albedo, but which also concentrates the absorption towards the top of the cloud. The heating rate at cloud top is thus slightly higher than that for the Analytic distribution, despite the fact that the overall cloud absorption is lower. The optical depth of the Analytic distribution is much smaller with the result that the absorption is spread more evenly through the cloud. The heating rate profiles obtained by using the parametrizations derived above are shown by the dots. The liquid water content and equivalent radius were read in for each cloudy level and the single scattering properties in each band were calculated within the program from Eqs. (15 to 17). The heating rates are very close to the 'exact' profiles, although in both examples the cloud top heating rate is overestimated. The inset tables show that the parametrized data provide good estimates of the cloud absorption and system albedo. The errors amount to about 10% of the difference between the properties of the two distributions, suggesting that this approach is capable of reproducing the cloud radiative properties to a reasonable accuracy.

Figure 9. An example of the use of Eqs. (15) – (17) to parametrize the single scattering properties of cloud drops, for band 22.
Figure 10. Comparison of the heating rate profiles obtained for the St II and Analytic drop size distributions in the Mid-latitude atmospheric profile. The heating rates obtained by using the parametrizations developed in section 5 are shown as the filled dots.

The sensitivity of these results to the specification of the asymmetry factor was explored by repeating the exact calculations with the asymmetry factor set to 0.85 in all spectral bands. The resulting errors in the cloud absorptions and system albedos were no larger than those arising from the use of the parametrizations described above. This shows clearly that the dependence of cloud short-wave properties on this parameter is extremely weak and that improvements in the parametrizations should concentrate on the extinction coefficient and single scattering albedo. More drop size distribution data may also be needed to refine the parametrizations, as they are based on only a few distributions and were not tested with an independent sample.

6. DISCUSSION

It has been shown that the short-wave single-scattering properties of typical cloud drop distributions can be parametrized in terms of simple functions of the liquid water content and equivalent radius and that these parametrizations can be used in a multiple scattering radiation scheme to derive the cloud radiative properties to a reasonable accuracy. The importance of this result stems from the fact that observations show a strong dependence of the drop size distribution on height within clouds. The computation time required to calculate the single-scattering properties of such clouds directly from Mie theory would be far in excess of that required by the radiation scheme. Such parametrizations therefore allow realistic cloud structure to be modelled by the scheme with a trivial increase in computer time. Results from a detailed aircraft study of stratocumulus using this approach will be presented in a subsequent paper (Slingo et al. 1982b). For boundary layer clouds in which the liquid water content is close to the adiabatic profile, it has also been demonstrated that absorption by the cloud drops is much more important than that by water vapour. Water vapour absorption could therefore be neglected with only a small error and, as Stephens (1978a) points out, this results in a further saving in computer time as it removes the need to sub-divide each spectral band.

The short-wave properties of clouds depend strongly on the liquid water path and
solar zenith angle. Stephens (1978b) and Liou and Wittman (1979) show that this dependence can be parametrized for use by the simpler radiation schemes employed in General Circulation Models. The present results illustrate the additional dependence on the drop size distribution and the sensitivity to the relative amounts of water vapour and liquid water. Cloud absorption also depends on several other factors, such as surface albedo, the temperature and water vapour profiles and the presence of other cloud layers. It is doubtless possible to extend the parametrizations to allow for all these effects, but if it is considered that they need to be treated then it may be better to incorporate a fast multiple scattering scheme into such a model and thereby calculate the cloud radiative properties directly. Liquid water content and the equivalent radius could be specified externally for maritime and continental clouds and for a limited selection of cloud types. Such a scheme could also be used if liquid water content was held as an additional model variable.

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