Broadband solar fluxes and heating rates for atmospheres with 3D broken clouds

By HOWARD W. BARKER¹†, JEAN-JACQUES MORCETTE² and G. DAVID ALEXANDER³

¹Atmospheric Environment Service, Canada
²ECMWF, UK
³Universities Space Research Association, USA

(Received 6 February 1997; revised 6 October 1997)

SUMMARY

A 3D Monte Carlo photon transport algorithm is presented that computes broadband solar fluxes and heating rates. It treats attenuation by cloud droplets and gases separately and can produce 3D distributions of constituent absorptances. Underlying surfaces are accounted for and diurnal-mean calculations can be achieved in the same time as typical single-zenith-angle experiments. Domain-averaged fluxes and heating rate profiles are presented for two very different 3D cloud fields: (i) scattered, shallow cumuli inferred from Landsat imagery; and (ii) towering clouds simulated by a cloud-resolving model. Plane-parallel, homogeneous (PPH), independent column approximation (ICA), and clear-sky versions of the 3D fields were generated and used as well.

For both cloud fields, total atmospheric absorptance depends very weakly on cloud geometry. Cloud geometry does, however, invoke major differences in surface absorptance and, hence, reflectance to space. At high sun, albedos for 3D clouds are less than corresponding PPH values, but are in almost perfect agreement with ICA estimates. This indicates that simple horizontal variability of cloud optical depth outweighs the impact of cloud sides. At very low sun 3D fields reflect most because of interception of radiation by cloud sides, while PPH and ICA albedos come into better agreement. For the towering cloud field, radiative fluxes are determined largely by clouds below 6 km, despite some clouds reaching 12 km. Heating rate profiles are also affected by cloud geometry. For most sun angles, PPH clouds exhibit anomalously large heating near cloud tops and anomalously small heating beneath clouds. On the other hand, profiles for 3D and ICA fields are very similar and depend much less on altitude; partly because of side illumination but also because the dense cores of inhomogeneous clouds are often radiatively-shielded (unlike their PPH counterparts).

Finally, regular arrays of idealized cloud forms are used to demonstrate the potential ambiguity of using cloud radiative forcing ratios, $R$, as proxy measures for the impact of clouds on atmospheric absorptance. In essence, $R$ depends not only on how clouds influence atmospheric absorption, but also on how they partition radiation between albedo and transmittance.

KEYWORDS: Atmospheric radiation Monte Carlo modelling Parametrization

1. INTRODUCTION

Since general circulation models (GCMs) consider clouds to be plane-parallel and homogeneous (PPH), and because in many regions broken, heterogeneous clouds are the rule, several theoretical studies sought to, and did, demonstrate that fields of inhomogeneous and PPH clouds transport solar radiation differently (e.g. Harshvardhan and Thomas 1984; Welch and Wielicki 1984, 1985; Kobayashi 1989; Barker and Davies 1992a). In these studies clouds were characterized by idealized, simple geometries (e.g. regular arrays of homogeneous cuboids) and so it is unclear to what extent their results have coloured our impressions of the PPH biases that are bound to occur in GCMs. Moreover, these studies addressed only monochromatic, conservative-scattering albedo and transmittance. Hence, knowledge is still limited regarding differences in broadband solar radiative transfer between realistic 3D clouds and their PPH counterparts. This, therefore, compromises debate over the partition of solar radiation incident on the earth (cf. Stephens and Tsay 1990; Li and Leighton 1993).

The issue of partitioning incident solar energy had its profile raised recently by Cess et al. (1995) and Ramanathan et al. (1995) who claimed that cloudy atmospheres absorb substantially more (∼25 W m⁻² on average) than predicted by conventional models. Li et al. (1995) countered these claims in part, by suggesting that if this anomalous absorption

* Corresponding author: Atmospheric Environment Service, Cloud Physics Research Division (ARMP), 4905 Dufferin St., Downsview, ON, Canada M3H 5T4. e-mail: howard.barker@ec.gc.ca.
† Additional affiliation: Dalhousie University, Canada.
TABLE 1. AMOUNTS OF GASES ASSUMED TO
BE PRESENT FOR ALL SIMULATIONS, AND TEM-
PERATURE AND PRESSURE SCALING EXPO-
NENTS $\zeta$ AND $\xi$.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Amount</th>
<th>$\zeta$</th>
<th>$\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2O</td>
<td>—</td>
<td>0.45</td>
<td>0.90</td>
</tr>
<tr>
<td>CO2</td>
<td>350 p.p.m.v.</td>
<td>0.375</td>
<td>0.75</td>
</tr>
<tr>
<td>O1</td>
<td>0.25 atm-cm</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>O2</td>
<td>20.948%</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CH4</td>
<td>1.72 p.p.m.v.</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>N2O</td>
<td>$310 \times 10^{-3}$ p.p.m.v.</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NO2</td>
<td>1.0 p.p.m.v.</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CO</td>
<td>8 p.p.m.v.</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Amounts and profiles for water vapour vary from simulation to simulation.

exists, it appears to be confined to warm climates where cumuliform clouds govern solar budgets (Warren et al. 1988; Ockert-Bell and Hartmann 1992). Thus, they hypothesized that realistic cloud geometries might enhance total atmospheric absorption relative to PPH estimates. However, using a 4 spectral band Monte Carlo (MC) algorithm that accounted for absorption and scattering, they acknowledged that, while this was true sometimes, enhancements were far less than those claimed by Cess et al. (1995) and Ramanathan et al. (1995).

On the other hand, using a stochastic radiative-transfer model for binary mixtures of finite clouds with water vapour absorption, Byrne et al. (1996) suggested that effects of finite clouds explain about half of the enhanced absorption claimed by Cess et al. (1995) and Ramanathan et al. (1995). Inspired by Byrne et al. (1996), a more detailed version of the MC algorithm used by Li et al. (1995) has been developed to elaborate on the results of Li et al. (1995), and investigate differences in solar heating profiles and fluxes between 3D cloud fields and their simplified counterparts.

In section 2 the MC algorithm is presented. Section 3 presents flux and heating rate results for 3D, PPH, independent column approximation, and clear-sky versions of two realistic, but very different, 3D cloud fields. Also in section 3, regular arrays of idealized cuboidal clouds are used to demonstrate ambiguities in using cloud radiative forcing ratios as indicators for anomalous cloud absorption. Concluding statements are made in section 4.

2. MONTE CARLO RADIATIVE-TRANSFER ALGORITHM

This section consists of five subsections. The first two describe the MC radiative-transfer algorithm used in this study and parametrizations employed in it. The third subsection discusses some computational issues while the fourth addresses the use of simplified versions of 3D atmospheres. The last subsection presents a brief validation of the algorithm.

(a) Theory and model description

The algorithm considers scattering by cloud droplets and air molecules, and absorption by droplets, water vapour, O3, and the uniformly mixed gases (UMGs): CO2, O2, CH4, N2O, NO2, and CO. Table 1 gives the amounts of gases assumed to be present, and temperature and pressure scaling components $\zeta$ and $\xi$ for computing effective absorber amounts: $u^* = u(T_{ref}/T)^\zeta (P/P_{ref})^\xi$, where $u$ is amount of gas and $T_{ref} = 296$ K,
\( P_{\text{ref}} = 1013.25 \) mb, and \( T \) and \( P \) are temperature and pressure at mid-layer. Atmospheres are divided into 3D lattices of cells with cyclic horizontal boundary conditions. Within each cell, all constituents are assumed to be homogeneous.

The probability of a photon of wavelength \( \lambda \), incident at the top of the atmosphere (TOA) with zenith angle \( \theta_0 (\mu_0 = \cos \theta_0) \), surviving after being scattered by \( n_{\text{ecl}} \) cloud droplets and traversing effective optical pathlengths \( u_1^* \) through \( N_k \) absorbing gases is

\[
\mathcal{P}(\lambda) = \omega_0^{n_{\text{ecl}}(\lambda)}(\lambda) \prod_{i=1}^{N_k} e^{-k_i(\lambda)u_i^*},
\]

where \( \omega_0 \) is droplet spectral single-scattering albedo (assumed here to be constant but in the model it can vary), and \( k_i \) are spectral gaseous-absorption coefficients. Then, if a spectral band from \( \lambda_j \) to \( \lambda_{j+1} \) is sufficiently narrow that cloud optical properties can be considered as constants across the band, the probability of an ensemble of photons surviving is

\[
\mathcal{P}_j = \omega_0^{n_{\text{ecl}}j} \left\{ \frac{\int_{\lambda_{j}}^{\lambda_{j+1}} S(\lambda) \prod_{i=1}^{N_k} e^{-k_i(\lambda)u_i^*} \, d\lambda}{\int_{\lambda_{j}}^{\lambda_{j+1}} S(\lambda) \, d\lambda} \right\}
\]

\[
\approx \omega_0^{n_{\text{ecl}}j} \left\{ \prod_{i=1}^{N_k} \frac{\int_{\lambda_{j}}^{\lambda_{j+1}} S(\lambda) e^{-k_i(\lambda)u_i^*} \, d\lambda}{\int_{\lambda_{j}}^{\lambda_{j+1}} S(\lambda) \, d\lambda} \right\} = \omega_0^{n_{\text{ecl}}j} \left\{ \prod_{i=1}^{N_k} \mathcal{I}_{i,j}(u_i^*) \right\}
\]

where \( S(\lambda) \) is the extraterrestrial solar spectrum (Labs and Neckel 1970), defined here between \( 0.25 \mu m \) and \( 4.0 \mu m \), and \( \mathcal{I}_{i,j}(u_i^*) \) is the \( j \)th band transmittance function for the \( i \)th gas. The approximation made in (2) is usually invoked for flux computations (Ramaswamy and Freidenreich 1992) and the narrower the band, the better the approximation.

Computation of broadband solar fluxes and heating rates requires that the spatial decay of \( \mathcal{P}_j \) be integrated (via the MC method) over the spectral, conditional-probability spaces of all model parameters. This is achieved by injecting a large number of photons \( N \) into the experiment, simulating photon paths, and reducing \( \mathcal{P}_j \) accordingly. If

\[
s_j = \frac{\int_{\lambda_{j}}^{\lambda_{j+1}} S(\lambda) \, d\lambda}{\int_{0.25 \mu m}^{4 \mu m} S(\lambda) \, d\lambda},
\]

is the fraction of the solar spectrum between \( \lambda_j \) and \( \lambda_{j+1} \), \( s_j N \) photons are injected for the \( j \)th waveband. Thus, CPU time required to compute broadband fluxes is independent of the number of spectral intervals. This differs from analytic models which have to perform full simulations for each band regardless of \( s_j \).

Since \( \theta_0 \)-specific and diurnal-mean experiments can be performed, photons enter experiments with initial weight \( \mu_0 \). Also, because boundary fluxes and tropospheric heating rates are of concern here, it is assumed that all the \( O_3 \) exists above the uppermost layer, above which no scattering occurs. Thus, down to the top of this layer, photon weight is \( \mu_0 \mathcal{I}_{3,j}(u_3^*) \) where \( u_3^* = u_{O_3}/\mu_0 \) in which \( u_{O_3} \) is the vertical depth of \( O_3 \). Below this level scattering by air molecules and cloud droplets can occur, and \( u_i^* \) through water vapour and the UMGs are accumulated. When a photon arrives at the surface a uniform random number between 0 and 1, hereinafter denoted as \( R \), is generated. If \( R \) exceeds the spectral surface albedo, the photon’s trajectory is terminated and \( \mathcal{P}_j \) is added to surface absorptance; otherwise it is unattenuated and reflected. The surface can be modelled as either a Lambertian, a Fresnelian, or a particulate reflector (Barker and Davies 1992b). To save CPU time, photons are terminated in the atmosphere when \( \mathcal{P}_j \ll 10^{-5} \).
If the \( n \)th photon exits the TOA, its weight (probability of survival) is

\[
\mathcal{P}_j(n) = \mu_0 \mathcal{T}_{3,j} \left( u_{0 \alpha} \left( \frac{1}{\mu_0} + \frac{1}{|\mu|} \right) \right) \mathcal{T}_{1,j} (u_1^*) \mathcal{T}_{2,j} (u_2^*) \left[ \prod_{n_{\text{cd}}=0}^{N_{\text{cd}}} \omega_{0j} \{ r_\varepsilon(n_{\text{cd}}) \} \right],
\]

(4)

where \( u_1^* \) and \( u_2^* \) are cumulative effective optical pathlengths for water vapour and UMGs, and \( \mu \) is the cosine of the photon's existing zenith angle. Note that transmittances for UMGs depend on CO\(_2\) amount only; concentrations of the other UMGs are fixed (see Table 1). In (4) \( \omega_{0j} \) depends on the effective radius \( r_\varepsilon \) of the droplet responsible for the \( n\text{th} \) scattering event of which there are \( N_{\text{cd}} \) in total. If \( N_{\text{cd}} = 0 \), the bracketed term in (4) equals 1. Spectral values of TOA albedo are defined by summing \( \mathcal{P}_j(n) \) for all reflected photons and dividing by \( \sum_{n=1}^{N_{\text{cd}}} \mu_0(n) \). Spatial distributions of spectral surface and atmospheric absorptances are accumulated through the simulation (i.e., losses to \( \mathcal{P}_j \)). Broadband TOA albedo is obtained by summing all reflected \( \mathcal{P}_j(n) \) and dividing by \( \sum_{n=1}^{N_{\text{cd}}} \mu_0(n) \). Corresponding values of surface absorptance and atmospheric absorptance are again accumulated through the run.

For diurnal-mean experiments one has to: (i) specify latitude \( \theta_L \) and day number \( J \); (ii) find the hour angle \( \theta_h \) between sunrise and noon; and (iii) inject photons at cosines of zenith angles

\[
\mu_0 = \sin \delta(J) \sin \theta_L + \cos \delta(J) \cos \theta_L \cos(\Delta \theta_h),
\]

(5)

where \( \delta(J) \) is solar declination (i.e., a uniform random sampling of time). When computing heating rates and fluxes for fixed \( \mu_0 \), solar flux incident on a perpendicular plane at the TOA is 1370 W m\(^{-2}\), but for diurnal-mean calculations, it depends on \( J \) (Spencer 1971). In addition, for all experiments reported here solar azimuth angles were selected at random for each injected photon (i.e., azimuthal averages).

Geometric distances between scattering events are determined by assigning transmittance at random and accumulating air molecule and cloud droplet optical depths (e.g., Welch et al. 1980). When a scattering event occurs, the choice between molecule or droplet depends on the relative magnitude of their local extinction coefficients. Figure 1 shows how absorptances at, and between, scattering events are computed. Accumulating attenuation by droplets and intervening gases in individual cells enables fractional absorptances and heating rates to be calculated for each constituent in each cell.

\(b\) Parametrizations

Band transmittance functions \( \mathcal{T}_{i,j} \) for gases other than O\(_3\) were derived from the 1992 HI-TRAN database (Rothman et al. 1992) assuming a Malkmus band model. Correspondingly, absorption coefficients for O\(_3\) were computed from cross-sections compiled by Molina and Molina (1986) for the ultraviolet, Anderson and Mauersberger (1995) for the visible, and Burkholder and Talukdar (1994) for the near-infrared regions. All \( \mathcal{T}_{i,j} \) were parametrized with Padé approximants as

\[
\mathcal{T}_{i,j}(u_1^*) = \frac{\sum_{k=0}^{K-1} c_{k;i,j}(u_1^*)^k}{\sum_{k=0}^{K} d_{k;i,j}(u_1^*)^k},
\]

(6)

where \( c \) and \( d \) are coefficients. Use of Horner's algorithm (Demidovich and Maron 1973) to evaluate (6), and noting that typically \( K \leq 3 \), makes for rapid computation of \( \mathcal{T}_{i,j} \). For this study \( S(\lambda) \) in (2) was resolved into 375 bands each of width 0.01 \( \mu \)m. Given this resolution the approximation in (2) is easily justified for the majority of bands.
Spectral optical depths of air molecules for the entire column are approximated by (Hansen and Travis 1974)

$$\tau_{j}^{\text{air}} = 0.008569 \bar{\lambda}_{j}^{-4} (1 + 0.0113 \bar{\lambda}_{j}^{-2} + 0.00013 \bar{\lambda}_{j}^{-4}),$$  

(7a)

where

$$\bar{\lambda}_{j} = \frac{\lambda_{j} + \lambda_{j+1}}{2}.$$  

(7b)

Thus, optical depth in the $m$th layer is simply $\tau_{j}^{\text{air}}(p_{m+1} - p_{m})/p_{1}$ where $p_{m}$ and $p_{1} = 1013.25$ mb are atmospheric pressures at level $m$ and the surface. Also for air molecules $\omega_{0} = 1$, and the cosine of the scattering angle is parametrized, based on Rayleigh’s phase function, as

$$\mu_{s} = \frac{1.1656(1 - 2R)}{1.1656 - R(1 - R)},$$  

(8)

which yields a maximum error for the scattering angle of $0.37^\circ$ (and again $R$ is a random number between 0 and 1).
Spectral optical properties for liquid cloud droplets are determined accurately and efficiently with Slingo's (1989) 24-band parametrizations for values of $r_c$ from 4.2 μm to 16 μm. Hence, cloud liquid water content (LWC) and $r_c$ are needed for each cloudy cell. Droplet scattering patterns are described by the Heneyy-Greenstein (1941) function using values of asymmetry parameter $g$ from Slingo's parametrization and

$$
\mu_s = \frac{1}{2g} \left\{ 1 + g^2 - \left( \frac{1 - g^2}{1 + g - 2gR} \right)^2 \right\},
$$

which is valid for all $g$ except 0. This is justifiable (Hansen 1969) since only fluxes are reported here.

(c) Statistical significance of fluxes

If for a single cloud field one performs an ensemble of MC experiments, each using a large number $N$ of photons, the absolute standard error for a fractional flux $F$ is defined as

$$
\sigma = \sqrt{\frac{(1 - F)F}{N}},
$$

and the relative standard error (%) is

$$
\sigma_{rel} = 100 \sqrt{\frac{(1 - F)}{NF}}.
$$

For this study, only domain-averaged, broadband fluxes and heating rate profiles were considered. Therefore, $N = 250,000$ and $N = 1,000,000$ were used to compute boundary fluxes and heating profiles, respectively. This usually yielded $\sigma_{rel} \leq 0.5\%$ for fluxes and $\leq 1.0\%$ for heating rates (given the layer thicknesses used).

(d) Simplified counterparts to 3D atmospheres

One of the main objectives of this study was to assess how well simplified treatments of radiative transfer mimic 3D results. The simplest approach is the PPH method as used in GCMs. Typically GCMs have horizontal resolutions greater than 100 km, and treat layer clouds as extensive PPH slabs that cover a fraction of a cell. Thus, the concern with PPH models is the lack of information about cloud variability at scales that are vitally important for radiative transfer; neglect of fluxes through the sides of columns with GCM proportions is irrelevant.

Two types of PPH representations were considered here. However, both operate on a common atmosphere generated from a 3D variable atmosphere by: (i) finding the mean optical depth $\tau_{cd}$ of clouds in each layer; (ii) assigning $\tau_{cd}$ to all cloudy cells in the layer; and (iii) making the horizontal dimensions of every cell arbitrarily large ($> 10^6$ km), thus creating negligible probability of a photon leaving the column it was incident on. The first type of PPH experiments, denoted as PPH(overlap), are achieved by injecting photons directly into the field just described. In such a way overlap of PPH clouds is represented perfectly. In practice, GCMs are not privy to this information. For the second type, denoted as PPH(random), photons are injected into the same field as used for PPH(overlap), but when a photon crosses a layer boundary or is reflected by the surface its horizontal coordinates are redefined at random. This eradicates cloud correlations in the vertical,
and effectively yields random cloud overlap (i.e. the natural representation in 1D analytic models (Morcrette and Fouquart 1986)).

Another popular simplified approach is the independent-column (or pixel) approximation (ICA). In the ICA, a 1D radiative-transfer model is applied to each column, regardless of column width, and results are integrated horizontally to give domain-averaged fluxes. This approach is likely to be used in cloud-resolving models which can have horizontal grid spacings of <1 km (e.g. Fu et al. 1995). While it may be safe at these grid spacings to assume that cells are either filled or free of clouds, thus largely addressing the issue of cloud overlap, each narrow column is assumed, erroneously, to be radiatively sequestered from neighbouring columns. In this study ICA simulations are achieved by simply making the horizontal grid spacings of inhomogeneous 3D fields arbitrarily large (>10 km).

Finally, it is instructive to compare cloudy-sky fluxes to corresponding clear-sky fluxes. Here, clear-sky atmospheres are obtained by setting the LWC of all cells to zero (i.e. cloud radiative forcing (CRF) method II; see Potter et al. 1992). Note that for cells in which LWC is set to zero water vapour is not altered, thus producing saturated cloudless cells.

(e) Monte Carlo verification

Table 2A lists the mean and root-mean-square (r.m.s.) difference for broadband fluxes predicted by about 21 models that participated in the InterComparison of Radiation Codes for use in Climate Models (ICRCCM; Fouquart et al. 1991); also listed are corresponding estimates from the MC method presented here. All cases are for the midlatitude summer (MLS) atmosphere with 300 parts per million by volume (p.p.m.v.) of CO₂; they are cloudless, and test gas parametrizations, Rayleigh scattering, and surface reflectance. From Table 2A, it is clear that this MC code falls within ranges of conventionally accepted values. To test the cloud parametrizations in the MC code, PPH clouds were considered. Table 2B lists absorptances within a cloudy layer of an atmosphere containing water vapour. The MC algorithm presented here is in excellent agreement with other models.

3. Results

This section is comprised of three main parts: the first two present results for two realistic cloud fields; the third illustrates how ratios of cloud radiative forcings can be misleading indicators for the impact of clouds on atmospheric absorption. All heating rate profiles and fluxes reported here are domain averages. Moreover, in addition to total heating rate profiles, heating rates are reported for water vapour inside and outside of clouds as well as for droplets.

(a) Realistic 3D atmospheres: shallow cumuli from Landsat imagery

In the subsection, results are presented for the field of shallow cumuli shown in Fig. 2. Optical depths for this field were derived from 28.5 m resolution Landsat imagery (Harshvardhan et al. 1994; Barker et al.'s (1996) scene C8) assuming rₚ = 10 μm. Due to memory limitations, however, horizontal resolution was degraded to 114 m. This should not affect results much, as cloud fluctuations below 100 m are expected to have minor impacts on domain-averaged fluxes (see Barker 1996b). Vertically-projected cloud fraction Aₑ is 0.46, and the frequency distribution of τ follows very closely a decaying exponential with a mean of 3.94. Solar zenith angle at viewing was 32°. All cloud bases were assumed to
be 300 m above a Lambertian surface with spectral independent albedo of 0.06. Cloud vertical thickness (in metres) for each column was prescribed by

$$z = 45.2 \tau^{2/3},$$  \hspace{1cm} (11)

and rounded to the nearest 75 m (rounded up to 75 m for columns with $z < 75$ m) which was the vertical resolution of this experiment. The relation in (11) approximates that reported by Minnis et al. (1992) and leads to a mean cloud thickness of $\sim 150$ m (2 layers) with the thickness column ($\tau \approx 48$) being 600 m (8 layers). Assuming each column to be vertically homogeneous, the thickest one had an extinction coefficient of $\sim 80$ km$^{-1}$ while the most likely value was $\sim 25$ km$^{-1}$ (cf. Stephens and Platt 1987). Table 3 lists the profile of cloud fraction $A_c$. This field was embedded in the MLS atmosphere (McClatchey et al. 1972) with saturation inside clouds. Outside of clouds, relative humidities ranged from 62% to 74%. For this cloud field, only results for the PPH(overlap) experiments are shown, as results from both PPH experiments resembled each other closely.

Figure 3(a) shows that the clear-sky heating profiles depend only weakly on altitude. Enhanced clear-sky heating near cloud bases is because saturated cells, formerly cloudy cells, are now irradiated by direct-beam radiation. Figure 3(a) also shows heating due to water vapour outside of clouds. For $\mu_0 = 1$, the 3D field shows the greatest extra-cloud
heating because of photon leakage from finite clouds; photons emerging from sides tend to have downward trajectories (see Welch and Wielicki 1984). Extra-cloud heating for the ICA field is generally less than for the PPH field. This is because ICA clouds are less reflective than PPH clouds (cf. Cahalan et al. 1994; Barker et al. 1996) and this gives rise to weaker return flows of photons, and thus heating rates, through cloudless cells above clouds.

By $\mu_0 = 0.5$, extra-cloud heating by the 3D and PPH fields is similar through most cloud bearing altitudes. This is due to: (i) reduced numbers of side-emergent photons with downward trajectories for 3D clouds; and (ii) reduced direct-beam incident on water vapour near cloud bases for 3D clouds. By $\mu_0 = 0.1$, the ICA and PPH profiles are almost equal because cloud albedos are becoming similar at such an oblique sun angle, and besides, extra-cloud heating is determined largely by the long slant paths for direct beams (which are virtually equal for these cases). Heating for the 3D field is now clearly the least. This
Table 3. Layer cloud fractions as a function of height above surface for the Landsat-inferred field shown in Fig. 2.

<table>
<thead>
<tr>
<th>Layer altitude (m)</th>
<th>Cloud fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>825–900</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>750–825</td>
<td>0.001</td>
</tr>
<tr>
<td>675–750</td>
<td>0.004</td>
</tr>
<tr>
<td>600–675</td>
<td>0.012</td>
</tr>
<tr>
<td>525–600</td>
<td>0.037</td>
</tr>
<tr>
<td>450–525</td>
<td>0.095</td>
</tr>
<tr>
<td>375–450</td>
<td>0.214</td>
</tr>
<tr>
<td>300–375</td>
<td>0.461</td>
</tr>
<tr>
<td>225–300</td>
<td>0</td>
</tr>
<tr>
<td>150–225</td>
<td>0</td>
</tr>
<tr>
<td>75–150</td>
<td>0</td>
</tr>
<tr>
<td>0–75</td>
<td>0</td>
</tr>
</tbody>
</table>

This demonstrates the impact of cloud shadows at large solar zenith angles, even for shallow clouds such as these.

Byrne et al. (1996) maintain that almost half of the anomalous cloud absorption as claimed by Cess et al. (1996) can be explained by increased photon pathlengths through and thus heating by, water vapour between 3D clouds. Figure 3(a), however, shows that for this case, this effect is quite minor.

Figure 3(b) shows that heating by water vapour inside clouds is much greater than that outside clouds. This is because inside clouds conditions are saturated, and also because scattering by droplets increases pathlengths through vapour (especially notable near cloud tops at \( \mu_0 = 1 \)). For overhead sun, the 3D clouds show weakest absorption for most cloud layers on account of loss of photons through side leakage. Commensurate with the trend shown in Fig. 3(a) for extra-cloud heating as a function of \( \mu_0 \) for 3D clouds, Fig. 3(b) shows that side interception of photons by 3D clouds becomes evident by \( \mu_0 = 0.5 \) and very notable at \( \mu_0 = 0.1 \).

Figure 3(c) shows that at high sun, droplet heating for 3D clouds is distinctly less than that for the other clouds. This is due, again, to side leakage with, in addition to reducing the number of photons, reduces the number of droplet scattering events. For oblique sun, 3D absorptances increase dramatically with altitude due to side injection of direct-beam photons; exactly as for vapour inside clouds. Both the ICA and PPH heating rates inside clouds are almost independent of altitude at \( \mu_0 = 0.1 \).

Thus, while large differences can exist in heating due to various components for different cloud geometries, it is clear from Fig. 3(d) that differences in total heating set up by different cloud geometries are relatively minor. This is because the largest differences are due to heating within clouds near cloud tops, i.e. in regions where clouds are sparse (see Table 3).

Figure 4 shows solar-zenith-angle dependent dispositions of solar radiation. Differences between TOA albedo and surface absorptance for the PPH and ICA fields have been referred to as PPH biases (see Cahalan et al. 1994; Barker et al. 1996; Oreopoulos and Davies 1997) and arise from horizontal variable \( \tau \). As expected, the ICA always reflects less and transmits more than the PPH. For both TOA albedo and surface absorptance, 3D and ICA values are in excellent agreement for \( \mu_0 \geq 0.35 \), implying that cloud sides are not important. For smaller \( \mu_0 \), however, side interception of photons becomes increasingly
important (see Figs. 3(b) and 3(c)) and the 3D field reflects more, and transmits less, relative to the ICA. Only for \( \mu_0 \leq 0.2 \) does the 3D field reflect more than the PPH; these results are reversed for surface absorptance (see Fig. 4(c)).

Despite sizeable differences shown in Figs. 3, 4(a), and 4(c), Fig. 4(b) shows that total, all-sky atmospheric absorptances are almost independent of cloud geometry and exceed clear-sky values by typically just 10%. Recently the ratio \( R \) of surface to TOA CRFs has been used to indicate the impact of clouds on atmospheric absorption (Cess et al. 1995; Ramanathan et al. 1995; Li et al. 1995). Utilizing CRF method II (Potter et al. 1992) and values shown in Figs. 4(a) and 4(c), Fig. 5 shows \( R \) as a function of \( \mu_0 \) for the cloud fields used thus far. These values are quite large by GCM standards, which are usually near 1.05 (Cess et al. 1995). The reason for this is that these clouds are saturated, and also the MLS atmosphere puts too much water vapour above boundary
layer clouds and so clouds resemble a highly reflective ground surface which enhances $R$ (cf. Li et al. 1995). Nevertheless, $R$ for the 3D field generally exceeds, but only by a few percent, the ICA and PPH values (which are virtually identical) despite the fact that for $\mu_0 > 0.5$, 3D absorptances are slightly less than PPH values. This alludes to the ambiguity of using $R$ as a proxy for the impact of clouds on total atmospheric absorptance (i.e. in addition to absorptance, $R$ depends on the relative partition of radiation between albedo and transmittance which depends in turn on cloud geometry).

(b) **Realistic 3D atmospheres: a cloud-resolving mesoscale convective system simulation**

In this section, MC results are presented for an atmosphere derived from a numerical simulation of the tropical mesoscale convective system (MCS) known as EMEX9 (e.g. Webster and Houze 1991). Thus, the purpose of this section is to investigate solar flux
characteristics for a cloud field containing towering clouds with realistic distributions of both cloud water and water vapour.

Since the EMEX9 simulation is documented in detail by Alexander (1995), it is described only briefly here. The simulation was done with the non-hydrostatic version of the Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992). Only the 1.5 km horizontal resolution inner-grid was used here. Each layer, therefore, consisted of 80 by 96 cells and so the domain was 120 km by 144 km. There were 34 layers of variable geometric thickness. All quantities in all cells were assumed to be homogeneous, and the lower boundary condition was a Lambertian reflector of albedo 0.06. The experiment reported here considered only cloud liquid water and water vapour. Ice, rain, snow, graupel and aggregates were neglected: rain is usually beneath deep clouds and is not important for radiation while snow, graupel, and aggregates tend to exhibit weak extinction. Ice, however, can be important but was neglected in order to maximize the effects of 3D distributions of liquid water; ice blanketed the domain and served to attenuate differences between 3D and PPH.

Since this experiment did not carry $r_e$, it was assumed, for simplicity, to be 10 $\mu$m everywhere. Obviously this inflates extinction coefficients inside towering clouds by a factor of $\sim 3$, as $r_e$ should be at least 30 $\mu$m (Stephens 1978). On the other hand, 10 $\mu$m is reasonable for shallower clouds and, as demonstrated later, the impact of the smaller shallower clouds is dominant.

While model fields are available for every 15 minutes, the field used here had most clouds sufficiently far from the domain’s edges. This minimized spurious signals that may arise via the MCs cyclic boundary conditions. Table 4 lists some key statistics of the field. Figures 6 and 7 show cloud optical depths (at $\sim 0.5$ $\mu$m) and cloud top altitudes. Clearly, this atmosphere is characterized by extreme 3D variability: a scattering of towering clouds (with droplets up to $\sim 12$ km and associated $\tau > 1000$) surrounded by numerous relatively
TABLE 4. Summary of properties for the EMEX9 scene shown in Figs. 6 and 7.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertically-projected cloud fraction</td>
<td>$A_c = 0.45$</td>
</tr>
<tr>
<td>Mean cloud optical depth</td>
<td>$\bar{\tau} = 116.5$</td>
</tr>
<tr>
<td>Mean natural logarithm of $\tau$</td>
<td>$\ln \tau = 3.26$</td>
</tr>
<tr>
<td>$\nu = (\bar{\tau}/\sigma^2)$ where $\sigma$ is the standard deviation of $\tau$</td>
<td>$\nu = 0.38$</td>
</tr>
<tr>
<td>Mean precipitable water</td>
<td>$p = 8.32$ g m$^{-2}$</td>
</tr>
</tbody>
</table>

Figure 6. Column-integrated cloud optical depths at 0.5 $\mu$m (due to liquid droplets) for the EMEX9 field (see text) considered here.

shallow clouds. This atmosphere has precipitable water vapour amounts typically between 7 and 9 g m$^{-2}$ which is roughly double that of the standard tropical atmosphere (McClellan et al. 1972).

Figure 8 shows the frequency distribution of $\tau$. Also plotted are the gamma distribution based on the mean and standard deviation of $\tau$ (cloudy columns only) and a distribution obtained from Cahalan et al.'s (1994) bounded-cascade model. It is encouraging that the idealized distributions fit the model-generated one so well. Following Stephens et al.
(1991), if $p(\tau)$ is a probability density distribution for $\tau$ and $R_{pp}$ is PPH albedo, let

$$R_{pp}(\eta \tau) \approx \int_0^\infty p(\tau) R_{pp}(\tau) \, d\tau,$$

(12)

where $\eta (\equiv e^{\text{frac}{\tau}})$ is the reduction factor needed for a PPH model to yield albedos close to that of a field with horizontal variable $\tau$ (Cahalan et al. 1994). From Table 4 the field in Fig. 6 has $\eta \approx 0.22$. Cahalan et al. and Barker et al. (1996) showed that $\eta$ is unlikely to be much less than 0.5 for marine boundary-layer clouds; but as surmised by Cahalan et al., a global mean (energy-weighted) value of $\eta$ is possibly close to 0.3. As such, values of $\eta < 0.3$ for tropical cloud fields may be typical (cf. Oreopoulos and Davies 1997). This suggests that the EMEX9 field used here may be a fair example of typical convective cloud fields.

Figure 9 shows total heating rate profiles for three values of $\mu_0$ for the 3D field shown in Fig. 6 and its associated PPH(random), ICA and clear-sky counterparts. The distinguishing feature between 3D and PPH is that the PPH profiles are more variable, particularly for high sun. This is so for two reasons. First, since PPH clouds are infinite in horizontal extent, their tops are very pronounced and photons incident on them tend
Figure 8. Frequency distribution of optical depth for the EMEX9 field; shown in Figs. 6 and 7. Also shown is a distribution generated by a bounded-cascade model (14 bifurcations) using $f_0 = 0.75$ (variance parameter) and $c = 0.794$ ($-5/3$ scaling) (see Cahalan et al. 1994), and a normalized gamma-distribution density function (Barker et al. 1996) whose parameters were based on the mean and variance of the EMEX9 optical depths (see Table 4). See text for further explanation.

Figure 9. Total, broadband heating rate profiles for the EMEX9 field shown in Figs. 6 and 7 along with its corresponding PPH(random), ICA, and clear-sky fields. Results for three solar zenith angles are shown (values of $\mu_0$ are shown on the plot). See text for further explanation.
to experience many scattering events, longer paths, and thus higher probabilities of being absorbed. With 3D clouds, however, photons can leak out of the sides which curtails droplet scattering events, optical pathlengths, and heating. As in the Landsat case, this is accentuated by the fact that, at a given altitude, the deepest parts of 3D clouds tend to be near the centre of towers, whereas more abundant thinner clouds around towers tend to be exposed to direct solar beams. This results in weak 3D cloud top heating. Conversely, all PPH clouds at a given altitude have the same \( \tau \), which can be quite large. Hence, the exposed thin 3D clouds are now exposed moderately thick PPH clouds. As a consequence, highly attenuative PPH clouds suppress transmittance, and this is manifest in a dramatic reduction in heating near and below cloud bases. The second reason why the 3D profile is smoother, is because photons can enter cloud sides and thus contribute to cloud heating well below cloud tops. This mitigates heating rate differences between the top and below-top regions. On the other hand, having no sides limits PPH cloud heating below tops, as discussed earlier.

Somewhat surprisingly, heating rate profiles for the ICA and 3D cases are very similar. Resemblance is closest for overhead sun, indicating that for this field flux profiles are governed more by simple horizontal variability of \( \tau \) than by 3D effects. At \( \mu_0 = 0.5 \) between 3 km and 9 km (primary cloud-bearing altitudes), ICA clouds have the lowest heating rates. This is because, unlike 3D clouds, ICA clouds do not experience side-injection of photons, and also because those cells in ICA clouds that are exposed to the direct solar beam are often thin relative to corresponding PPH cells, and so ICA clouds tend to generate fewer scattering events. Heating profiles for the PPH field with proper cloud overlap (not shown) are, almost without exception, between the PPH(random) and ICA profiles.

Figure 10 shows a more detailed picture of heating by 3D and PPH clouds at overhead and very oblique sun. At \( \mu_0 = 1.0 \), 3D clouds transmit more radiation than their PPH counterparts because of horizontal variable \( \tau \) (see Cahalan et al. 1994; Barker 1996a) and also because of side-emergent photons (Welch and Wielicki 1984). This leads to enhanced heating outside of clouds below \( \sim 5 \) km (Fig. 10(a)). On the other hand, heating outside PPH cloud is greatest above 6 km because of highly reflective clouds near 6 km. At \( \mu_0 = 0.1 \), the PPH field has a slightly larger extra-cloud absorptance as 3D values are then reduced due to cloud shadows. Figures 10(b) and 10(c) show that, in concert with side-interception at \( \mu_0 = 0.1 \), 3D heating by both vapour inside clouds and cloud droplets is often at least twice as large as corresponding PPH values.

Figure 11 shows solar-zenith-angle dependent values of TOA albedo, atmospheric absorptance, and surface absorptance for 3D, PPH(random), PPH(overlap), ICA clouds and clear skies. As with the Landsat case, for high sun conditions the overwhelming effect is that of horizontal variable \( \tau \), as values for 3D and ICA clouds are very similar while corresponding PPH(overlap) albedo is about 25% larger and PPH(random) is, typically, a staggering 60% too large. These differences exceed greatly the largest PPH biases reported for marine stratocumulus cloud (cf. Cahalan et al. 1994; Barker et al. 1996). Moreover, had the horizontal resolution been better than 1.5 km these differences would have been larger, as 3D and ICA albedos would have then been smaller than those in Fig. 11. As \( \mu_0 \) decreases, TOA albedo for the 3D case increases sharply (even exceeding PPH(random) for very small \( \mu_0 \)) on account of interception of photons by cloud sides (see Fig. 8 of Barker and Davies 1992a). Meanwhile, the ICA curve diverges from the 3D yet is always less than, but almost parallel to, the PPH(overlap) curve. Results for surface absorptance are qualitatively identical but reversed in sign.

Echoing results presented earlier, all versions of the cloud field have remarkably similar values of atmospheric absorptance for all sun angles, except for the PPH(random)
Figure 10. As Fig. 9 but showing heating rates (K day$^{-1}$) due to (a) water vapour outside and (b) inside of clouds, and (c) cloud droplets; (d) gives the sums of these three profiles weighted by their fractional area per layer, i.e. the total heating rates. Results are shown only for the 3D and PPH(random) fields for the two values of $\mu_0$ shown in (d). See text for further explanation.

case which has the largest absorptance (presumably stemming from amplified multiple internal reflections). Even the clear-sky curve differs only slightly from three of the cloudy curves, and on a diurnal-mean basis the four quantities differ by amounts that are probably immeasurable ($<5$ W m$^{-2}$). This again testifies to the robustness of the vertical integral of absorption.

Figure 12 shows zenith-angle dependent values of $R$ for the four cloud fields. $R$ decreases with $\mu_0$ simply because at oblique sun, clouds (particularly 3D clouds) shade water vapour in the lower troposphere which, in the absence of clouds, would have absorbed strongly. Despite this, $R$ exhibits very little dependence on cloud geometry. Note that had the clear-sky reference been, say, the standard tropical atmosphere (McClatchey et al. 1972), all values of $R$ would have been slightly larger than those shown here.

There is an alternative view of 3D cloud effects. Consider the following experiment: perform a clear-sky MC simulation (clouds eliminated but water vapour untouched); per-
form another simulation, but include only those clouds in the layer adjacent to the surface; repeat this process, adding cloud layers one by one until the entire cloud field is present. The sequence of radiation fields produced will elucidate the relative importance of clouds of increasing height.

Figure 13 shows overall radiation quantities for full 3D and PPH(random) clouds at two solar zenith angles (0° and 84.3°) for the EMEX9 field as a function of cloud top altitude (i.e. the altitude above which all clouds were removed). For overhead sun, bulk disposition of solar radiation is almost completely determined by clouds with tops below ~6 km. This corroborates the implications in Figs. 9 and 11 that, at high sun, the impact of deep clouds is very weak, and that the majority of the radiative signature arises from horizontal variability of $\tau$ for clouds with vertical geometric thicknesses generally less than 3 km. Moreover, it implies that towering clouds trap radiation reflected by lower clouds with an efficiency roughly equal, but opposite in sign, to that at which they themselves produce albedo.

These results are understandable, for in a region the size of a GCM grid-cell one can expect a small probability of very intense vertical motion, and hence very few occurrences
of extremely tall clouds. The other factor limiting the importance of towering clouds is that the majority of clouds above \( \sim 6 \) km sit atop clouds that are already optically thick. Thus, adding more cloud registers weakly. At very low sun the scenario is similar though the impact of clouds above 6 km is visible; quantities change notably right up to 12 km. This is because the cross-sectional area of towers presented to the sun can be quite large when \( \mu_0 \) is very small.

So, although towering clouds are critical for mass, energy, and momentum fluxes (Alexander 1995), they are of limited importance for solar radiative fluxes averaged over domains the size of GCM cells. This is not true, however, for extensive cirrus offspring from these rare events, as their radiative impacts can be huge and even dominant (they were not included here as the purpose was to examine the near upper-limit of the importance of 3D clouds).

(c) 3D cloud geometry and anomalous absorption

Results presented thus far imply that total atmospheric absorption of solar radiation is quite insensitive to cloud geometry. This is contrary to Byrne et al.'s (1996) conclusion that one-half of the cloud absorption anomaly reported by Cess et al. (1995) and Ramanathan et al. (1995) can be explained by enhanced photon pathlengths through water vapour between 3D clouds. However, some key points are in need of clarification. First, Byrne et al. used grid-averaged liquid water paths \( \mathcal{L} = 200 \) g m\(^{-2}\). Therefore, at \( A_c = 0.1 \), where their effect is strong, \( \mathcal{L} = 2000 \) g m\(^{-2}\). This trend in mean \( \tau \) with \( A_c \) is opposite to that observed (Luo et al. 1994; Barker et al. 1996) at least for marine boundary-layer clouds. Second, they claim that one-half of the cloud absorption anomaly can be explained by an effect that occurs for a narrow range of cloud field dimensions (\( \sim 1 \) km) at cloud fractions less than about 0.1. It is difficult to see how this can explain half of what Cess et al. (1995) maintain is a global anomaly. Third, the quantitative basis of their claim seems to rest on
being able to generate large values of $R$ for broken clouds. As pointed out by Li et al. (1995), and as shown in Figs. 4 and 5, $R$ can be an ambiguous measure of the impact of cloud on atmospheric absorption. Therefore, this subsection presents MC results for idealized cloud forms, and demonstrates the ambiguous nature of cloud radiative forcing ratios as indicators for cloud absorption anomalies.

Regular (checkerboard) arrays of identical, homogeneous cuboidal clouds were used. Horizontal and vertical grid spacings were 1 km and 0.25 km. Cloud bases were 1 km and tops 2 km above the surface, and each cloud measured 1 km in both horizontal directions with $r_e = 10 \mu m$ everywhere. Vertical distributions of water vapour, temperature, and CO$_2$ were set by the MLS atmosphere. Amounts of CO$_2$ and O$_3$ were as in Table 1. Inside clouds, saturation prevailed. Since incident solar azimuth angles were selected at random, results resemble those from a random array of clouds (cf. Kobayashi 1989; Barker 1991).
Using the conditions of Byrne et al. (1996) at $A_e = 0.0625$ (surface albedo of 0.2 and $\theta_0 = 40^\circ$, where their effect is maximized), the MC model presented here yields $R = 1.33$ for 3D clouds with a corresponding PPH value of 1.05. Total atmospheric absorption for the 3D field is largest by about 10 W m$^{-2}$ (i.e. consistent with Byrne et al.) but translates into a diurnal mean of $\sim 5$ W m$^{-2}$. These clouds have $S = 3200$ g m$^{-2}$ with TOA albedos for 3D and PPH clouds of 0.227 and 0.224. To make these very similar TOA albedos equal, $S$ for the 3D clouds was reduced to a mere $\sim 200$ g m$^{-2}$, thus leading to $R = 1.19$ and total atmospheric absorption exceeding the PPH value by 4 W m$^{-2}$ ($\sim 2$ W m$^{-2}$ for diurnal mean). As alluded to earlier, these, and Byrne et al.'s, values of $R$ would be reduced slightly if the amounts of water vapour above clouds were less than MLS values.

This experiment was repeated for the climatologically more relevant scenario of the diurnal mean for July 15 at 40°N, and results are listed in Table 5A. Relative to the case with $\theta_0 = 40^\circ$, differences in both $R$ and atmospheric absorption (24 hour averages) between the 3D and PPH cases are reduced by roughly 50%. Table 5B shows that when the surface is black differences are reduced even further, and when TOA albedos for 3D and PPH are equalized by reducing the 3D value of $S$, 3D and PPH behave almost identically. This illustrates the importance of $\alpha_s$; radiation reflected by the Lambertian surface in the PPH case is allowed easy access to space, while for 3D clouds cloud sides enhance both pathlengths through water vapour and the number of droplet scattering events. The larger $\alpha_s$ in the near infrared (IR) the greater this effect*, as seen in Table 5C where differences in $R$ reach 0.21 but atmospheric absorptions differ by just $\sim 3$ W m$^{-2}$.

* This may explain some of the large values of $R$ reported by Li et al. (1995). While months with mean TOA broadband albedo greater than 0.3 were eliminated, some cases with high near-IR $\alpha_s$ may have been retained.

<table>
<thead>
<tr>
<th>(A) $\alpha_s = 0.2$ (all bands)</th>
<th>clear sky</th>
<th>PPH</th>
<th>3D (3200 g m$^{-2}$)</th>
<th>3D (200 g m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{tou}$</td>
<td>0.1898</td>
<td>0.2249</td>
<td>0.2318</td>
<td>0.2262</td>
</tr>
<tr>
<td>$\alpha_{atm}$</td>
<td>0.6262</td>
<td>0.5885</td>
<td>0.5751</td>
<td>0.5836</td>
</tr>
<tr>
<td>$\alpha_{atm}$</td>
<td>0.1841</td>
<td>0.1867</td>
<td>0.1931</td>
<td>0.1902</td>
</tr>
<tr>
<td>$R(\Delta)$</td>
<td>—</td>
<td>1.07</td>
<td>1.22(+3.2 W m$^{-2}$)</td>
<td>1.16(+1.7 W m$^{-2}$)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(B) $\alpha_s = 0.0$ (all bands)</th>
<th>clear sky</th>
<th>PPH</th>
<th>3D (3200 g m$^{-2}$)</th>
<th>3D (135 g m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{tou}$</td>
<td>0.0556</td>
<td>0.0962</td>
<td>0.1160</td>
<td>0.0959</td>
</tr>
<tr>
<td>$\alpha_{atm}$</td>
<td>0.7704</td>
<td>0.7226</td>
<td>0.6970</td>
<td>0.7227</td>
</tr>
<tr>
<td>$\alpha_{atm}$</td>
<td>0.1740</td>
<td>0.1812</td>
<td>0.1870</td>
<td>0.1814</td>
</tr>
<tr>
<td>$R(\Delta)$</td>
<td>—</td>
<td>1.18</td>
<td>1.21(+2.8 W m$^{-2}$)</td>
<td>1.18(+0.1 W m$^{-2}$)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(C) $\alpha_s = 0.1$ ($\lambda \leq 0.7 \mu m$); $0.3 (\lambda &gt; 0.7 \mu m)$</th>
<th>clear sky</th>
<th>PPH</th>
<th>3D (3200 g m$^{-2}$)</th>
<th>3D (250 g m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{tou}$</td>
<td>0.1933</td>
<td>0.2278</td>
<td>0.2326</td>
<td>0.2272</td>
</tr>
<tr>
<td>$\alpha_{atm}$</td>
<td>0.6225</td>
<td>0.5824</td>
<td>0.5690</td>
<td>0.5786</td>
</tr>
<tr>
<td>$\alpha_{atm}$</td>
<td>0.1842</td>
<td>0.1898</td>
<td>0.1985</td>
<td>0.1942</td>
</tr>
<tr>
<td>$R(\Delta)$</td>
<td>—</td>
<td>1.16</td>
<td>1.37(+4.3 W m$^{-2}$)</td>
<td>1.30(+2.2 W m$^{-2}$)</td>
</tr>
</tbody>
</table>

Vertically-projected $A_e$ is 0.0625 and surface albedo(s) $\alpha_s$ are listed at the top of each table. Columns labelled PPH and 3D (3200 g m$^{-2}$) are for $S = 3200$ g m$^{-2}$. The last column is for the 3D clouds with adjusted $S$ such that its $\alpha_{tou}$ approximately equals the PPH value. $R$ is the ratio of surface to TOA CRF and $\Delta$ is the difference in atmospheric absorption (24 hour averages) going from the PPH field and the 3D fields.
As a final point, consider the following simple illustration. Define $R$ as

$$ R \equiv \frac{\alpha_{\text{sfc}}^{\text{clr}} - (\alpha_{\text{sfc}}^{\text{all}} + \varepsilon)}{1 - (\alpha_{\text{sfc}}^{\text{all}} + \varepsilon) - \alpha_{\text{atm}}^{\text{all}}} - \alpha_{\text{toa}}^{\text{clr}}, $$

where $\alpha_{\text{sfc}}^{\text{clr}}$ and $\alpha_{\text{sfc}}^{\text{clr}}$ are clear-sky surface absorptance and TOA albedo, $\alpha_{\text{sfc}}^{\text{all}}$ is all-sky surface absorptance, and $\alpha_{\text{atm}}^{\text{all}}$ is all-sky atmospheric absorptance (the term in braces is all-sky TOA albedo). $\varepsilon$ serves to modulate all-sky TOA albedo and $\alpha_{\text{sfc}}^{\text{all}}$ without altering $\alpha_{\text{atm}}^{\text{all}}$. Figure 14 shows $R$ as a function of $\varepsilon$ using values in (13) that are approximately equal to those for the 3D case in Fig. 4 at $\mu_0 = 1.0$. Since clear-sky atmospheric absorptance is 0.2, when $\alpha_{\text{atm}}^{\text{all}} = 0.2$, $R \approx 1$ regardless of $\varepsilon$. However, when $\alpha_{\text{atm}}^{\text{all}} > 0.2$, $R$ increases with $\varepsilon$ with increasing dependence on the larger $\alpha_{\text{atm}}^{\text{all}}$. This demonstrates clearly that, in addition to $\alpha_{\text{atm}}^{\text{all}}$, $R$ depends on the partition of radiation between $\alpha_{\text{sfc}}^{\text{all}}$ and $\alpha_{\text{toa}}^{\text{all}}$, which, as shown throughout this study, depends on cloud geometry. Thus, results in this section demonstrate that large values of $R$ do not necessarily indicate substantial enhancements of atmospheric absorption; $R$ increases when cloud transmittance is enhanced relative to PPH clouds, at the expense of reduced albedo.

4. SUMMARY AND CONCLUSION

A high spectral-resolution (375-band) Monte Carlo photon transport algorithm has been presented. It treats attenuation by cloud droplets and gases separately, and thus yields 3D distributions of absorptances due to different constituents. It accounts for several underlying surface models, and the cost of a diurnal-mean simulation equals that for a specific
solar zenith angle. Domain-averaged fluxes and heating rate profiles were presented for: a 3D field of shallow cumuli inferred from Landsat imagery; a 3D field of liquid and gaseous water as simulated by the RAMS cloud-resolving model (EMEX9); and idealized 3D cloud fields.

The main findings of this study can be summarized as:

- The necessarily limited results presented by Li et al. (1995) were corroborated; differences in domain-averaged, vertically integrated atmospheric solar absorptances between 3D cloud fields and their PPH counterparts tend to be small (i.e. <5 W m\(^{-2}\)). Hence, if anomalous absorption of solar radiation by clouds exists, similar to that reported by Cess et al. (1996), cloud geometry is unlikely to play an important role. This somewhat opposes the claim of Byrne et al. (1996); while their large values (>1.3) of \( R \) for sparse, individually dense 3D clouds were reproduced in the present study, associated increases in total atmospheric absorptances relative to PPH conditions were very limited. In other words, large differences in \( R \) do not necessarily imply anomalously large absorptances. It is important, however, to mention that experimental domain size can easily sway results. That is to say, the impact of towering clouds on local radiation budgets can be striking (cf. Barker and Li 1997).

- Total, domain-averaged heating rate profiles depend fairly weakly on cloud geometry. PPH clouds tend to have larger vertical gradients, primarily because their cloud tops are very pronounced and much exposed to direct-beam radiation. Moreover, their strong attenuation suppresses heating near the cloud base and beneath clouds.

- Unlike total atmospheric solar absorptances, net surface and TOA fluxes tend to differ markedly between realistic 3D clouds and their PPH counterparts. For moderate to high sun conditions, 3D clouds transmit more and reflect less radiation relative to PPH clouds. This could have a bearing on atmospheric stability, and may be important for climate modelling given the high frequency of occurrence of deep convective clouds in tropical and midlatitude summer regions (Warren et al. 1988). At low sun 3D clouds intercept more photons than PPH clouds on account of cloud sides. Thus, 3D fields reflect more radiation and have less surface heating. These conclusions were not surprising given previous experiments with near-conservative scattering (e.g. Welch and Wielicki 1984).

- Even for the EMEX9 field used here, which is clearly 3D in nature, the remarkable similarity between the dispositions of solar heating for independent-column clouds (i.e. clouds with horizontal variability but no sides) and 3D clouds suggests that accounting for horizontal variability of cloud optical depth \( \tau \) is crucial, and often sufficient, for domain-averaged flux calculations. In fact, overall radiative flux responses of the EMEX9 experiments were determined by the horizontal variability of clouds below 6 km, despite the presence of large towering clouds which reached 12 km. This importance of horizontal variable \( \tau \) is reminiscent of results for marine boundary-layer clouds (cf. the Landsat example in this study; Cahalan et al. 1994; Barker et al. 1996; Barker and Wielicki 1997) and should simplify GCM radiation parametrizations that attempt to account for subgrid-scale cloud variability (e.g. Oreopoulos and Barker 1998).

**ACKNOWLEDGEMENTS**

HWB is particularly grateful to Bruce Wielicki (NASA/Langley) for making computer time available. We also wish to thank B. Wielicki and L. Parker for providing Landsat data. Discussions with Z. Li, W. O’Hirok, and L. Oreopoulos, and comments by anonymous reviewers, helped shape this manuscript.
REFERENCES


Ockert-Bell, M. E. and Hartmann, D. L. 1992 The effect of cloud type on Earth’s energy budget: Results for selected regions. *J. Climate*, 5, 1157–1171


<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Reference</th>
</tr>
</thead>
</table>