Solar Radiative Transfer for Wind-Sheared Cumulus Cloud Fields

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ABSTRACT

The Monte Carlo method of photon transport was used to simulate solar radiative transfer for cumulus-like cloud forms (and cloud fields) possessing structural characteristics similar to those induced by wind shear. Using regular infinite arrays of finite, slanted-cuboidal clouds (parallelepipeds), it was demonstrated that the magnitude of cloud field albedo variation as a function of relative solar azimuth angle (up to 40° of albedo) can be larger than the albedo disparities between plane-parallel clouds and fields of nonsheared finite clouds. In general, cloud field albedo is maximized when shearing is away from the sun and minimized when shearing is toward the sun. This is explained by changes in effective cloud fraction presented to the direct solar beam. The albedo of individual clouds, on the other hand, is maximized when shearing is toward the sun, especially when shearing angle equals solar zenith angle. This is because of both reduced irradiance onto cloud sides and enhanced effective optical depth of cloud. These results were corroborated by conducting similar experiments using realistic cloud forms generated by a dynamical/microphysical cloud model. The magnitude of albedo differences between sheared and corresponding nonsheared broken clouds reached 25% of the albedo. Again, this is due to differing effective cloud fractions and side illumination.

It was found that the bidirectional reflectance functions (BDRFs) of sheared clouds are sensitive to solar azimuth angle. Relative differences between BDRFs for clouds sheared toward and away from the sun can be as large as 50% for arrays of idealized parallelepipeds and 25% for more realistic clouds. Differences are minimized when viewing is perpendicular to the wind shear direction provided clouds are sheared toward or away from the sun. BDRFs for sheared clouds are much more asymmetric near the zenith than BDRFs for corresponding cubic (nonsheared) clouds. Hence, viewing sheared clouds at a 60° zenith angle will not necessarily provide least biased estimates of cloud field albedo as is the case for nonsheared clouds. Finally, it was demonstrated that BDRF differences arising from use of Mie and Henyey–Greenstein phase functions are substantially smaller than differences associated with varying solar azimuth angle.

1. Introduction

The following statements are accepted tenets of modern climatology: the earth’s radiation budget at the top of the atmosphere is governed much by the interaction of solar radiation with liquid water clouds (Kiehl and Ramanathan 1990; Ockert-Bell and Hartmann 1992); global climate modeling studies suggest that the same is true for the earth’s overall surface energy budget (Randall et al. 1992); uncertainties regarding cloud–radiative forcing and feedbacks are prime hindrances in the quest for confident prediction of climatic change (Cess et al. 1989); comprehension of global distributions of cloud properties depends fully on modeling correctly radiative transfer in clouds (Rossow 1989). These statements have at least one essential feature in common: solar radiative transfer in water clouds. It is therefore imperative to develop rapid and accurate techniques for calculating solar radiative transfer for realistic clouds and cloud fields in conjunction with identification of the aspects of cloud geometry that have the greatest influence on radiative transfer.

Applied radiative transfer algorithms are based on the assumptions that clouds are plane parallel and homogeneous. These tractable algorithms are accurate provided the boundary conditions apply (King and Harshvardhan 1986). Real clouds, however, fall far short of satisfying these conditions. Thanks to numerous modeling efforts over the past two decades (Welch and Wielicki 1984; Cahalan 1989; Davis et al. 1990; Barker 1992), complacency has faltered with regard to the use of plane-parallel, homogeneous solutions of the radiative transfer equation.

The most blatant inhomogeneous, non-plane-parallel clouds are probably fields of well-defined cumulus clouds (be they lingering stratocumulus cells, fair-weather cumuli, or towering cumuli). Several studies have examined solar radiative transfer for various idealized arrays of cumulus clouds (Davies 1978; Welch and Wielicki 1985; Kobayashi 1988; Barker and Davies 1992). The overwhelming consensus with regard

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to both fluxes and radiances is that the "broken" nature of cloud fields significantly affects solar radiative transfer. While observational backing for these claims has not been so forthcoming, results from Stephens and Greenwald (1991) and Coakley (1991) suggest that the presence of large-scale geometric structures tends to reduce cloud field albedos and reflectances especially in the nonabsorbing region of the solar spectrum. They also suggest that large-scale geometric effects greatly outweigh effects due to microphysical structure (i.e., cloud droplet size distributions).

Among the aforementioned theoretical studies, the common and tacit broken cloud characteristic has been that individual clouds are portrayed best as vertical columns or perfect hemispheric domes. In essence, this implies an absence of wind shear, which is a reasonable assumption for marine stratocumulus and is indeed what many of the studies addressed explicitly. More often than not, however, the existence of wind shear and its impact on cloud shape cannot be neglected when dealing with fairweather cumuli, cumuli associated with cold air outflow over relatively warm surfaces, trade cumuli, and towering cumuli.

The purpose of the present paper is to report the effects that wind shear--induced geometry have on the transport of solar radiation for both fields of cumulus clouds and individual clouds. In section 2, the experimental design is outlined. In section 3, idealized regular arrays of clouds are used to illustrate the effects of wind shear on cloud albedo. These results are supported by similar calculations but using data from a sophisticated dynamical/microphysical cloud model. Section 4 examines the effects of wind shear--induced cloud geometry on cloud bidirectional reflectance functions, and concluding remarks are made in section 5.

2. Experimental design

Fluxes and radiances are computed with the Monte Carlo method of photon transport. The algorithm used was documented by Barker and Davies (1992). There are, however, some additions with regard to computation of bidirectional reflectances. The upward facing hemisphere is partitioned into \( N \) cells of equal angular area. Photons exiting the experiment are assigned to a specific cell. Bidirectional reflectance functions (BDRFs) are computed for each cell at the end of an experiment by dividing the total number of photons that exited into each cell by the number of photons that would have accumulated had the cloud field been a perfect Lambertian reflector with an albedo equal to that of the cloud or cloud field. All experiments reported here used surface albedo of zero. Furthermore, scattering and absorption of radiation by gases were neglected. Hence, computations apply best to measurements made at cloud top. Fractional differences in fluxes and BDRFs at cloud top are, however, similar to those at the top of the atmosphere if the atmosphere above the cloud layer is cloud-free.

Cloud geometry is portrayed two ways in this study. The first type of cloud is highly idealized and derives from horizontally infinite arrays of homogeneous, finite, vertical cuboids arranged in a regular checkerboardlike pattern (e.g., Welch and Wielicki 1984). The novelty of this study is that rather than being vertical cuboids, all the clouds in an array are slanted uniformly. Thus, they are parallelepiped cloud forms. Presumably, this captures the gross characteristics of wind shear geometric effects similar to the way in which regular arrays of cuboids capture the gross characteristics of broken stratocumulus.

The parallelepiped cloud forms consist of many vertical layers that are regularly offset in one horizontal direction such that the cloud edges make a well-defined angle \( \theta_s \) with respect to the zenith. Figure 1 illustrates what the resulting cloud field looks like. The cloud fields used in this study derive from \( \theta_s = 0^\circ \) being cubic clouds separated by one cloud width in the \( x \) direction and two cloud widths in the \( y \) direction (note that these are not the dimensions in Fig. 1). Hence, for this special case the vertically projected cloud fraction as a function of \( \theta_s \) is

\[
A_s(\theta_s) = \begin{cases} 
1 + \tan^2 \theta_s, & \theta_s \leq \theta_{\text{crit}} \\
1/2, & \theta_s > \theta_{\text{crit}},
\end{cases}
\]

(1)

where

\[
\theta_{\text{crit}} = 90^\circ - \arctan(1/2) \approx 63.5^\circ.
\]

Regular arrays of clouds with the shearing direction parallel to the cloudless "streets" between clouds were chosen because this is similar to what is often either

![Fig. 1](image-url). Schematic illustration of a portion of the idealized cloud field–sun geometry used in this study. Relevant angles are cloud shearing angle \( \theta_s \), solar zenith angle \( \theta_0 \), solar azimuth angle relative to the shearing direction \( \varphi_0 \), and reflected photon zenith \( \theta \) and azimuth \( \varphi \) angles.
observed (e.g., Wielicki and Welch 1986) or simulated (Chlond 1991). Other Monte Carlo–based experiments (Harshvardhan and Thomas 1984) have acknowledged this form in a much more idealized manner by fashioning clouds as infinitely long parallel bars.

If the finite clouds used here were not sheared ($\theta_s = 0^\circ$), their vertical optical depth would be $\tau$. When offsetting (shearing) occurs, however, the optical depth along their shearing axis is $\tau / \cos \theta_s$, and the average vertical optical depth of the cloud becomes

$$\bar{\tau} (\theta_s) = \begin{cases} \frac{\tau}{1 + \tan \theta_s}, & \theta_s \leq \theta_{\text{crit}} \\ \frac{\tau}{3}, & \theta_s > \theta_{\text{crit}}. \end{cases}$$  

Thus, as $\theta_s$ increases up to $\theta_{\text{crit}}$, average vertical cloud optical depth decreases, but the vertically projected cloud fraction increases so as to preserve cloud volume. Despite this, clouds in a field will be said to have an optical depth of $\tau$ regardless of $\theta_s$. For the sake of a tractable presentation of the main findings, results are presented primarily for clouds with $\tau = 40$ (some results for $\tau = 10$ are also presented). Furthermore, these idealized arrays of cumulus clouds are assumed to be internally homogeneous with a cloud droplet scattering function defined by the Heney-Greenstein (1941) function using an asymmetry factor of 0.85 and a single scattering albedo of 1.0, which are appropriate for visible radiation.

The second type of clouds used in this study are more realistic than those just described, for they were produced by a sophisticated dynamical/microphysical cloud model (Vaillancourt 1992). The cloud model is a 2D slab-symmetric version of Clark’s (1977, 1979) model, while the microphysical model is that due to Brengnien and Grabowski (1992). The outer domain of the model has $98 \times 98$ grid cells with resolution of 45 m, extends from the surface to 4.4 km, and has cyclical horizontal boundary conditions. The inner domain also has $98 \times 98$ grid cells, but their resolution is 15 m and its lower boundary is at $\sim$1.1 km. The position of the inner domain was chosen so as to contain the evolving cloud for as long as possible. A vertical wind shear of 3.0 m/s/km was specified upward of 1.4 km (where horizontal wind speed was nil). The cloud condensation nuclei concentration was assumed to be constant at 1000 cm$^{-3}$. This serves to make the effective radii of the cloud droplet size distributions (which vary between 1 and 15 $\mu$m) quite small ($\sim$4.5 $\mu$m), thus typifying a small, nonprecipitating continental cumulus cloud.

Optical properties of the cloud were computed using Mie scattering theory (Wiscombe 1979). Each grid cell was assigned an extinction coefficient based on its droplet size distribution and radiation wavelength of 0.6 $\mu$m. When a photon is scattered by a cloud droplet, the droplet radius is selected based on the cell’s droplet size distribution. Each droplet radius range has a specific single scattering Mie phase function. Three-dimensional clouds were constructed from the 2D model clouds by simply making the clouds homogeneous in the crosswind direction.

3. Results: Reflected fluxes

This section is devoted to analysis of cloud albedo while the next section focuses on reflected radiance patterns (bidirectional reflectance functions). This section begins by presenting results for the idealized regular array of slanted clouds. The main findings are then corroborated with results for the model clouds. The number of photons per flux experiment was 100,000. This leads to maximum errors for albedo of 0.0016.

Figures 2 and 3 show cloud field albedo $\alpha_c (\theta_0, \varphi_0; \theta_s)$ as a function of solar azimuth angle $\varphi_0$ for three different solar zenith angles $\theta_0$. Figure 2 is for clouds with $\theta_0 = 27^\circ$ and Fig. 3 is for clouds with $\theta_0 = 45^\circ$. Also shown in these figures are the fractions of direct solar beam intercepted by clouds $A_c (\theta_0, \varphi_0; \theta_s)$ [i.e., the cloud fraction that would be inferred from satellite data if the satellite were observing from the hot spot direction (Gerstl and Simmer 1986), also called effective cloud fraction; see Welch and Wielicki (1984)] as well as an approximation of the individual cloud albedo defined as

$$\alpha_c = \frac{\alpha_{\text{eff}} (\theta_0, \varphi_0; \theta_s)}{A_c (\theta_0, \varphi_0; \theta_s)}.$$  

Note that if $\theta_0 = 0^\circ$, $A_c (\theta_0, \varphi_0; \theta_s)$ becomes that given in (1). From here onward, the functional dependencies of $\alpha_c$, $\alpha_{\text{eff}}$, and $A_c$ should be understood to apply, but for brevity the notation will be eliminated.

Clearly, the variable affected most by changes in $\varphi_0$ is $A_c$, which in the cases of $\theta_s = 45^\circ$ and $\theta_s = 45^\circ$ and 60$^\circ$ (Fig. 3b and c) varies by $\sim$0.4. The general pattern of $A_c$ for $\theta_0 \leq 45^\circ$ is a slight increase from $\varphi_0 = 0^\circ$ to $\sim 45^\circ$ and a steady decline to $\varphi_0 = 180^\circ$. For $\theta_0 = 60^\circ$, however, the initial rise is much exaggerated, going from 0.5 at $\varphi_0 = 0^\circ$ [effectively horizontal bars of clouds; cf. Harshvardhan and Thomas (1984)] to $\sim$0.7 at $\varphi_0 = 45^\circ$. This is followed by an equally steep decline to a relative minimum of about 0.4 at $\varphi_0$ between 100$^\circ$ and 130$^\circ$, followed by a slight increase and again a decline to a minimum value at $\varphi_0 = 180^\circ$. Obviously, the details of these dependencies are specific to regular arrays of parallelepiped clouds and are governed much by cloud spacing and aspect ratio. The general trend, however, of $A_c$ being maximized near $\varphi_0 = 0^\circ$ and minimized near $\varphi_0 = 180^\circ$ may be expected for realistic cloud fields.

Comparison of the curves for $\alpha_c$ and $\alpha_{\text{eff}}$ confirm that changes in $A_c$ are mostly responsible for much of the variation in cloud and cloud field albedo. This is in agreement with previous studies that attempted to parameterize reflected fluxes for broken cloud fields: they addressed explicitly the effective cloud fraction (e.g.,
Welch and Wielicki 1985; Harshvardhan and Thomas 1984). Basically, \(\alpha_d\) is maximal for \(\varphi_0\) between 0° and 45° and minimal near \(\varphi_0 = 180°\). For the examples shown here at \(\tau = 40\), for a given solar zenith angle \(\alpha_d\) varies by \(-25\%\) and between 25\% and 45\% for \(\theta_e = 27°\) and 45°, respectively, as \(\varphi_0\) changes from 0° to 180°. While \(\theta_e = 45°\) is perhaps an extreme example, \(\theta_e = 27°\) is not. Therefore, a 25\% variation in albedo due simply to changes in \(\varphi_0\) appears to be feasible and is tantamount to the magnitude of albedo differences expected between plane-parallel clouds scaled for cloud amount and regular arrays of finite, nonsheared clouds [as well as scaling arrays of finite clouds; Barker and Davies (1992)]. For \(\theta_0 = 30°\), the albedo differences shown here are much greater than those between plane-parallel and regular arrays of clouds. Furthermore, these albedo differences are much greater than those expected to exist between homogeneous clouds and clouds with realistic internal variability over a wide range of scales, which is estimated to be less than 15\% (e.g., Barker 1992; R. F. Cahalan 1992, personal communication).
Table 1 lists albedos for the isolated clouds $\alpha_{iso}$ corresponding to the clouds used in Figs. 2 and 3, which are essentially

$$\lim_{A_c \to 0} \alpha_c,$$

where $A_c \to 0$ is affected by letting intercloud spacing go to infinity. The difference between $\alpha_c$ and $\alpha_{iso}$ is due to cloud shadowing and cloud–cloud interactions of photons. However, since $\alpha_{iso}$ is for the most part slightly less than $\alpha_c$ ($\approx 0.02$), the effects of cloud shadowing and cloud–cloud interactions in these examples are small. The notable exceptions are when $\theta = \theta_0$ at $\varphi_0 = 180^\circ$ and when $\theta = 45^\circ$, $\theta_0 = 60^\circ$, and $\varphi_0 = 0^\circ$. In the first two cases (Figs. 2a and 3b), $\alpha_{iso}$ is about 8% less than $\alpha_c$. Evidently, this is due to enhanced cloud–cloud interactions of photons (i.e., a significant fraction of photons exit cloud sides on trajectories just below the horizon). In the latter case, it can be shown that with this array of clouds the lower 15% of the clouds are in the shadow of their neighbor. Thus, photons are not incident near cloud base where trans-
mission is easiest. Also, photons that are transferred through the thin regions of the upper side of the cloud have a large probability of being intercepted by neighboring cloud sides; hence, $\alpha_c$ is greater than $\alpha_{\text{iso}}$.

The magnitude of the variations in $\alpha_{cf}$ due to changes in $A_c$ for $\varphi_0$ between $0^\circ$ and $180^\circ$ are ameliorated on account of $\alpha_c$ (and $\alpha_{\text{iso}}$) being anticorrelated with $A_c$. This is especially true when $\theta_s = \theta_0$. For example, in Figs. 2a and 3b when $\theta_s = 27^\circ$ and $\theta_0 = 30^\circ$ and $\theta_i = 45^\circ$ and $\theta_0 = 45^\circ$, $\alpha_c$ at $\varphi_0 = 180^\circ$ exceeds that at $\varphi_0 = 0^\circ$ by about $20\%$ ($0.61$ compared to $0.50$) with much of the variation occurring between $\varphi_0$ of $120^\circ$ and $180^\circ$. For $\theta_s = 27^\circ$ and $\theta_0 = 45^\circ$ (Fig. 2b) and $\theta_s = 45^\circ$ and $\theta_0 = 30^\circ$ (Fig. 3a), however, $\alpha_c$ is almost independent of $\varphi_0$. This pattern is explained as follows.

Figure 4 shows a side view of the cloud field used here with $\theta_s = 27^\circ$, $\theta_0 = 30^\circ$, and $\varphi_0$ of $0^\circ$ and $180^\circ$. At $\varphi_0 = 0^\circ$, the average optical depth parallel to the incident beam is much less than at $\varphi_0 = 180^\circ$. For $\varphi_0 = 0^\circ$, $\tau$ parallel to the direct beam is always less than $40/\cos 30^\circ$ since $\theta_0 > \arctan(1 - \tan \theta_0)$. Furthermore, a significant fraction of the irradiated cloud face has very thin edges, which allows photons easy passage. For $\varphi_0 = 180^\circ$, however, very little radiation impinges on the sides of the cloud and $\sim 87\%$ of the incident beam encounters cloud where $\tau$ parallel to the incident beam is $40/\cos 30^\circ$. Thus, it is clear why in this case, $\alpha_c$ is greater at $\varphi_0 = 180^\circ$. The importance of side illumination leading to suppression of $\alpha_c$ can be appreciated by noting that when $\theta_0$ is $60^\circ$ and $\varphi_0$ is between $90^\circ$ and $120^\circ$, side illumination is confined to near the tops of clouds due to shadowing by neighboring clouds (note that area of cloud-top irradiance is unchanged). In these illumination conditions, $\alpha_c$ is relatively large compared to that for values of $\varphi_0$ just outside of this range. All of these factors serve to enhance the difference between $\alpha_c$ (and $\alpha_{cf}$) at $\varphi_0$ of $0^\circ$ and $180^\circ$.

Figures 5a–c shows the effective cloud fraction, cloud field albedo, and cloud albedo for the same cloud field used in Figs. 2 and 3 except there is no shearing effect (clouds are vertical cubes $\theta_i = 0^\circ$). These results have a $90^\circ$ periodicity rather than $180^\circ$ as in the sheared cases. Previous studies that used cuboidal clouds presented results for $\varphi_0$ of $0^\circ$ (or equivalently $90^\circ$ and $180^\circ$). Clearly, those studies represent minimum reflectances for regular arrays since for $\varphi_0 = 0^\circ$, effective cloud fraction is minimized (maximum reflectances occur at $\varphi_0 = 45^\circ$). Since those studies showed that in general broken clouds reflect more than their plane-parallel counterparts for $\theta_0 > 30^\circ$, Fig. 5 demonstrates that the disparity between broken and planar clouds is probably slightly more than previously thought (for smaller $\theta_0$, albedos are practically independent of azimuth). From the results presented in Figs. 2, 3, and 5, it can be said that albedos of nonsheared clouds depend much less on $\varphi_0$ relative to that for sheared clouds. For the results shown here, for $\varphi_0$ between $0^\circ$ and $180^\circ$ and a constant $\theta_0$, $\alpha_{cf}$ varies by just $5\%$ to $15\%$ for nonsheared clouds as opposed to $25\%$ to $45\%$ for sheared clouds. Again, this is primarily because effective cloud fraction of the nonsheared clouds depends relatively weakly on solar azimuth. This effect far outweighs the fact that the sheared clouds show a stronger anticorrelation between effective cloud fraction and $\alpha_c$ (and $\alpha_{\text{iso}}$) than do nonsheared clouds.

Figure 5d shows differences between the cubic and the sheared cubes [i.e., $\alpha_{cf}(\theta_0 = 0^\circ)$ and $\alpha_{cf}(\theta_0 \neq 0^\circ)$]. Positive values mean that standard cubic cloud arrays reflect more than the arrays of sheared clouds. The general trend is that fields of sheared clouds reflect more for $\varphi_0 \leq 90^\circ$ and less for $\varphi_0 \geq 90^\circ$. This is due mostly to variations in effective cloud fraction that are large compared to variations in $\alpha_c$. Absolute fractional differences in $\alpha_{cf}$ for $\varphi_0$ near $0^\circ$ and $180^\circ$ are approximately $25\%$. Integration of the deviations over all $\varphi_0$, however, yields small differences in $\alpha_{cf}$ between sheared and nonsheared cloud fields: the sheared fields reflect about $5\%$ to $10\%$ more in these cases. Hence, in a climatological sense, there may be little difference between sheared and nonsheared cloud field albedos.

![Fig. 4. Side view of idealized sheared clouds with $\theta_s = 27^\circ$. Solar beams are incident at $\theta_i = 30^\circ$ for $\varphi_0 = 0^\circ$ and $180^\circ$. Maximal vertical $\tau$ is 40 and the shaded regions show where $\tau$ measured parallel to the direct beam is less than $40/\cos 30^\circ$. The heavy solid line on the plane perpendicular to the solar beam for $\varphi_0 = 180^\circ$ indicates where $\tau$ measured parallel to the direct beam is equal to $40/\cos 30^\circ$. It constitutes $\sim 87\%$ of the incident beam.](image-url)
Table 2 lists values of $\alpha_c$ for the same cloud fields used thus far but with $\theta_s = 27^\circ$ and $\tau = 10$. Comparing the values in this table with the curves in Fig. 2 shows that the qualitative dependencies of $\alpha_c$ (and $\alpha_c$) on $\varphi_0$ are similar for $\tau$ ranging from 10 to 40. Also listed in Table 2 are values of $\alpha_c$ for cubes with $\tau = 10$ as a function of $\varphi_0$. Comparing part (a) of Table 2 to part (b) shows that the dependence of $\alpha_c$ on $\varphi_0$ is much greater for the slanted clouds than for their cubic counterparts (same as for $\tau = 40$).

It is worth noting at this stage that as $A_c$ increases, the intricate geometric effects shown here are suppressed steadily by cloud–cloud interactions (Welch and Wielicki 1985). For very large $A_c$ there is little difference between sheared, nonsheared, and plane-parallel clouds.

The preceding results for regular arrays of idealized sheared clouds suggest that the ramifications of wind shear on cloud geometry may lead to cloud and cloud field albedos depending substantially on solar
Table 2. (a) Cloud field albedos for the field of slanted clouds used in Fig. 2 ($\theta_c = 27^\circ$) but with $\tau = 10$ rather than 40 (therefore, $\overline{\tau} = 6.6$; see Eq. (2)). (b) As in (a) except $\theta_c = 0^\circ$ (i.e., regular cubes).

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(a)

(b)

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azimuth relative to the shearing direction (i.e., synoptic flow at cloud level). In order to partially back this claim, the Monte Carlo photon transport method was used to calculate cloud albedos for clouds produced by the detailed cloud model as described in section 2.

Figure 6 shows the cloud form between 42 and 49 min into the simulation (the cloud appeared at 36 min). The width of the clouds in the crosswind direction is set constant at the length of the cloud in the wind-tracking direction at 38 min. This implies no mixing in the crosswind direction. At 42 min there is little asymmetry, though the cloud is beginning to bulge on the upshear side and smaller droplets due to entrainment of clear air exist on the downshear side (Vaillancourt 1992). By 43 min, however, the cloud developed and maintained approximately a 30° slant downwind. By 49 min, the cloud became thoroughly mixed. Figure 7 shows the vertically integrated optical depth at 0.6 µm. At 42 min average cloud optical depth $\overline{\tau}$ is 41. At 44 min $\overline{\tau}$ peaks at 48 and by 49 min $\overline{\tau}$ has decreased to 29. Note, however, that $\tau$ actually reaches a maximum of 120 near the center of the cloud at 46 and 47 min. From 42 to 48 min, cloud aspect ratio varies between 0.59 and 0.73. These values are similar to the idealized clouds, which have aspect ratios of 0.66 and 0.5 for $\theta_c$ of 27° and 45°. In all cases, the aspect ratio is defined as the ratio of the total geometric lengths spanned by the cloud in the vertical and wind-tracking direction.

Figure 8 shows cloud albedo $\alpha_{iso}$ as a function of time for $\theta_c = 30^\circ$ and $60^\circ$ at $\varphi_0$ of 0° and 180°. Due to the near symmetry of the cloud at 42 min, $\alpha_{iso}$ is almost independent of $\varphi_0$. However, for $\theta_c = 30^\circ$ during 43 to 48 min, $\alpha_{iso}$ at $\varphi_0 = 180^\circ$ exceeds that at $\varphi_0 = 0^\circ$ by about 10% to 25%. This is very similar to the differences in both $\alpha_{c}$ and $\alpha_{iso}$ as calculated for the regular arrays at $\theta_s = 27^\circ$ (see Fig. 2a and Table 1). These differences are again due to overly thin regions exposed to direct beam at $\varphi_0 = 0^\circ$ in contrast to an effectively very solid core at $\varphi_0 = 180^\circ$ as well as light side illumination at $\varphi_0 = 180^\circ$.

For $\theta_c = 60^\circ$ at 43 and 44 min, $\alpha_{iso}(\varphi_0 = 0^\circ)$ is slightly greater than $\alpha_{iso}(\varphi_0 = 180^\circ)$ by an amount very similar to that for the idealized parallelepipeds clouds.

![Fig. 6. Outline of evolving cloud as predicted by the cloud model between 42 and 49 min into the simulation (6 to 13 minutes after the cloud first appeared). Grid containing the cloud is the (1.5 km)$^2$ region where resolution is 15 m.](image)
Fig. 7. Vertically integrated cloud optical depth for the clouds shown in Fig. 6. Values are for incident radiation of 0.6 μm.

(see Table 1). Figure 6 shows that this is when the clouds most resemble the ideal clouds. For 47, 48, and 49 min, $\alpha_{\text{iso}}(\varphi_0 = 180^\circ) > \alpha_{\text{iso}}(\varphi_0 = 0^\circ)$; the reasons for this are abundantly clear from Fig. 6. At 47 min, the main body of the cloud is becoming separated from a smaller portion near the base. Since in the experiments performed in this study gaps between pieces of clouds were taken to be part of the entire cloud, many photons were allowed unchecked passage through holes at $\varphi_0 = 0^\circ$. Whether such holes should be considered as part of the cloud is open to debate and underlies one of the major difficulties associated with experimental estimation of cloud absorption (Barker 1992).
angles of 0° and 180° (see Fig. 1). Results are presented for parallelepiped clouds first and more realistic clouds second. The number of photons per BDRF experiment was 1 000 000.

Figures 9a and 10a show BDRFs for an array of idealized parallelepiped clouds with $\theta_0 = 27°$, $\varphi_0 = 0°$, and $\theta_0 = 30°$ and 60°. These arrays are the same as those used in section 3. For $\theta_0 = 30°$ (Fig. 9a), the BDRF is

![Image of Figure 8](image-url)

Fig. 8. Albedo as a function of time for the clouds shown in Fig. 6. Solid lines are for $\varphi_0 = 0°$ (sun coming in from the left side on Fig. 6) and the broken lines are for $\varphi_0 = 180°$.

In summary, the form of albedo sensitivity for idealized, sheared clouds as a function of solar azimuth angle has been substantiated by results for much more realistic clouds, which possess substantially greater variability than just definite sides and simple shearing deformation. It should be noted, however, that the albedo sensitivity for the more realistic clouds was slightly less than that for the idealized clouds.

4. Results: Bidirectional reflectances

This section focuses on the disparity between bidirectional reflectance functions (BDRFs) for sheared clouds and associated cloud fields given solar azimuth

![Image of Figure 9](image-url)

Fig. 9. (a) Polar plot of BDRF for an array of idealized parallelepiped clouds slanted at 27° to the zenith. Cloud optical depth in the absence of slanting is 40, normally projected cloud fraction is 0.25, incident solar zenith angle (SZA) $\delta_0$ is 30°, and clouds are sheared away from the sun ((AZI) $\varphi_0 = 0°$). Shaded region is for BDRF > 1.0. (b) As in (a) except clouds are sheared toward the sun ($\varphi_0 = 180°$). (c) Difference between (a) and (b): BDRF($\varphi_0 = 0°$) - BDRF($\varphi_0 = 180°$).
Greenstein (1941) phase function. That the BDRF for \( \theta_0 = 30^\circ \) and \( \theta_t = 27^\circ \) is similar to that for \( \theta_0 = 60^\circ \) and \( \theta_t = 0^\circ \) could be anticipated since in both cases \( \theta_0 + \theta_t \) are almost equal and, hence, the relative proportion of top-to-side illuminations are similar. In Fig. 10a where \( \theta_0 = 60^\circ \), there is an excess of backscattered radiation relative to Breon’s (1992) and Davies’s (1984) case on account of \( \theta_0 + \theta_t = 90^\circ \): a large fraction of photons are incident on the sides of the slanted clouds.

Figures 9b and 10b show the BDRFs for \( \varphi_0 = 180^\circ \) at \( \theta_0 = 30^\circ \) and \( 60^\circ \). Comparison of these plots to their counterparts at \( \varphi_0 = 0^\circ \) shows that for \( \theta_0 \leq 50^\circ \) the patterns have reversed their nature about the \( \varphi = 90^\circ \) line: minima are in the backward hemisphere and forward scattering is much intensified. This is readily apparent from Figs. 9c and 10c, which show differences between BDRFs for \( \varphi_0 = 0^\circ \) and \( 180^\circ \). This is because at \( \varphi_0 = 180^\circ \), most photons are incident on the tops of the clouds (especially at \( \theta_0 = 30^\circ \)), which tend to reflect similar to plane-parallel clouds (forward scattering is pronounced), while the few photons that are incident on cloud sides arrive at very oblique angles and tend to exit the same side traveling downward (cf. Welch and Wielicki 1984; Breon 1992). This suppresses backscatter even at \( \theta_0 = 60^\circ \) where side incidence is similar to that at \( \theta_0 = 30^\circ \) and \( \theta_t = 0^\circ \). The result is that for \( \varphi_0 = 180^\circ \), a large proportion of reflected photons are in the forward hemisphere. Figures 9 and 10 show that differences in BDRFs can be as large as 50\% (Fig. 9 at \( \theta = 50^\circ \) and \( \varphi = 150^\circ \)) depending on whether the clouds are sheared towards or away from the sun.

Figure 11 shows BDRF differences for the same conditions used in Figs. 9 and 10 except these are for isolated clouds, not arrays of clouds. For isolated clouds relative to arrays of clouds, BDRF differences are exaggerated most notably in the backward direction \( \varphi \sim 180^\circ \). This is because backscatter is suppressed much when neighboring clouds intercept photons exiting close to the horizon. Thus, removal of neighboring clouds leads to a substantial increase in backscattered radiation and an increase in the fraction of photons incident on cloud sides when \( \theta_0 \) is large. That BDRF differences in the forward scattered direction between isolated clouds and arrays of clouds are small indicates that most of the forward scattered photons exit from or near cloud tops and are rarely intercepted by neighboring clouds.

Figure 12 shows BDRFs differences between \( \varphi_0 = 0^\circ \) and \( 180^\circ \) for the isolated realistic cloud at \( t = 44 \) and 45 min. The state of the cloud at these times is much like the parallelepiped cloud: approximately a 30\(^\circ\) slant; average vertical optical depth of 45; and aspect ratio of 0.65 (at \( \theta_t = 30^\circ \), the aspect ratio of the parallelepiped clouds is 0.66). Comparing these plots to those in Fig. 11 suggests that the BDRF differences obtained with the parallelepiped clouds are of the cor-

\[\text{Fig. 10. (a), (b), and (c) As in Fig. 9 except } \theta_0 = 60^\circ.\]
rect sign but are approximately twice as large as those obtained with the realistic cloud. This is certainly due to the hemisphere-like crown of the realistic cloud. Such a cloud top will tend to make the contribution to the BDRF from near-cloud-top exiting photons less dependent on \( \varphi \); it is more symmetric than the harsh edges of the parallelepiped clouds and thus reflects similar to a Lambertian sphere (see Davies 1984). Nevertheless, near the horizons, close to the forward and backward directions, differences in Fig. 12 are substantial, and this is again due to the disparity in relative abundances of side illumination depending on whether clouds are sheared toward or away from the sun.

Another common feature seen in Figs. 11 and 12 is that the zero contour is close to \( \varphi = 90^\circ \) for \( \theta \leq 45^\circ \) but is displaced slightly into the forward hemisphere for \( \theta \geq 45^\circ \). For the arrays of clouds, zero differences are always close to \( \varphi = 90^\circ \) (or \( 270^\circ \)). This implies that if the viewing azimuth angle is close to being perpendicular to the sun—shearing direction plane, it makes little difference whether clouds are sheared toward or away from the sun: the BDRFs are similar. It is important to point out, however, that this is not likely a manifestation of the sharp cloud edges used here. While real clouds do not have angular edges, this will certainly influence the BDRF most notably near \( \varphi = 90^\circ \), but the effects will probably be similar for \( \varphi_0 = 0^\circ \) and \( 180^\circ \). Of course, if the clouds are sheared perpendicular to the sun, BDRFs are identical for \( \varphi_0 = 0^\circ \) and \( 180^\circ \).

Figure 13 shows BDRFs along the principal plane formed by the sun and the zenith for four types of clouds. Figures 13a and 13b are for isolated clouds and arrays of parallelepiped clouds, respectively, with \( \theta \) = 27\(^\circ\), while Fig. 13c is for the same arrays but clouds have \( \theta = 0^\circ \) (i.e., regular cubes). In Figs. 13a and 13b, minima in BDRF occur almost at \( \theta \) in the forward direction for \( \varphi_0 = 0^\circ \) and at \( \theta \) in the backward direction for \( \varphi_0 = 180^\circ \). The same is true for \( \theta = 0^\circ \) (Fig. 13c). Note that \( \theta \neq 0^\circ \) breaks the near symmetry of the BDRF for \( \theta \approx 45^\circ \). Thus, for small, and therefore important, viewing zenith angles (\( \theta < 30^\circ \)), BDRFs for sheared and nonsheared cloud fields can vary by up to 20\%–40\%. This could have substantial consequences for inferences of reflected fluxes and cloud attributes.

Figure 13d shows BDRFs for two forms of plane-parallel clouds corresponding to the clouds in Figs. 13a–c: first is an overcast cloud with optical depth \( \tau_{pp} = 6.7 = 40A_c = 0.167 \tau \) and the second is a plane-parallel cloud with \( \tau_{pp} = 40 \). If the second form of plane-parallel cloud is assumed to occupy 0.167 of a region, while the first form covers the entire region, the
Fig. 13. (a) BDRF in the principal plane as a function of viewing zenith angle (negative angles correspond to \( \varphi = 180^\circ \)) for an isolated idealized cloud with \( \theta_0 = 27^\circ \). Solar azimuth angles are labeled on the plot. Solid lines are for \( \theta_0 = 30^\circ \) and dashed lines are for \( \theta_0 = 60^\circ \).
(b) As in (a) except this is for an array of idealized clouds. (c) As in (b) but for an array of corresponding cubic clouds. (d) As in (c) except for two brands of plane-parallel clouds: overcast with an optical depth of 6.7 and fractional with an optical depth of 40 (i.e., plane parallel but scaled by a cloud amount of 0.167).

Comparison of BDRFs for these two forms is tantamount to Coakley and Kobayashi’s (1989) reflectance comparisons. While there are clear differences between these two forms, they are both very different from those shown in Figs. 13a–c except for the sheared clouds with \( \varphi_0 = 180^\circ \) and the overcast cloud with \( \tau_{pp} = 6.7 \); the BDRFs associated with these two cloud forms are quite similar for \(|\theta| < 50^\circ \). This is because it is the tops of the sheared clouds that are doing most of the intercepting and reflecting of photons.

As a final point to be made, Fig. 14 shows the difference between BDRFs for the realistic cloud at \( t = 45 \) min, \( \theta_0 = 45^\circ \), and \( \varphi_0 = 0^\circ \) when exact Mie and approximate Henyey–Greenstein phase functions are used. The Mie functions are characterized by a sharp forward-scattering peak and a backscattering peak,
whereas the Heney–Greenstein functions decrease monotonically from forward to backward scattering. This is evident in Fig. 14, where the difference in BDRFs is maximized in the backward hemisphere at $\theta$ close to $\theta_b$ (the low-order scattering hot spot). There is relatively little difference in the forward direction because phase function details are washed out due to multiple scattering. The maximum negative difference along the horizon near $\varphi = 120^\circ$ is likely due to the minimum in the Heney functions at roughly $110^\circ$ scattering angle. The main point of this plot is that the differences shown here due to treatment of microphysical scattering properties are approximately half those shown in Fig. 12, which are due to cloud geometry.

Figure 15 shows BDRFs along the principal plane for the Heney and Heney–Greenstein cases using $\varphi_0 = 0^\circ, 10^\circ, 30^\circ$, and $60^\circ$ with the realistic clouds at $t = 42, 45$, and $49$ min. The most noteworthy point here is the presence of the low-order scattering opposition effect (Hapke 1981) for the Heney cases (direct backscatter). Aside from this, both phase functions lead to quite similar BDRFs especially in the forward-scattered direction where reflected photons have experienced relatively many scattering events.

5. Summary and conclusions

Several studies have explored numerically the relative differences between solar radiative transfer for plane-parallel clouds and broken cloud fields (e.g., Welch and Wielicki 1984; Kobayashi 1988; Barker and Davies 1992). The general hypothesis is that relative to plane-parallel albedos scaled by cloud fraction, albedos for broken clouds are larger at low sun and smaller at high sun. This hypothesis has been supported to some extent by observations (Stephens and Greenwald 1991; Coakley 1991). Thus far, however, broken clouds have been portrayed as though they existed in the absence of wind shear. While this may be adequate for stratocumulus clouds, it is often not true for most other forms of cumulus clouds. The present study accounted for wind shear effects on the form of broken cumulus and used the Monte Carlo method of photon transport to demonstrate that such effects can have a significant impact on albedos and bidirectional reflectance patterns of clouds and cloud fields.

Idealized arrays of identical cubic clouds were used, but the clouds were slanted in a common direction to represent the gross effects of wind shear. It was demonstrated that cloud field and individual cloud albedos can be very sensitive to solar azimuth angle $\varphi_0$ measured relative to the shearing direction (Fig. 1). Generally, when clouds are sheared away from the sun, cloud field albedos are maximized and individual cloud albedos are minimized. The opposites are true when clouds are sheared toward the sun. For a given cloud field and solar zenith angle, albedo differences across the full range of $\varphi_0$ vary by $25\%$ to $40\%$ of the albedos. These are large differences that are comparable to, and often larger than, differences between nonsheared broken clouds and plane-parallel clouds (e.g., Welch and Wielicki 1984; Barker and Davies 1992). These calculations were corroborated by repeating the experiments with complex cloud forms obtained from a high-resolution dynamical/microphysical cloud model (Vaillancourt 1992). Furthermore, cloud field albedo differences between sheared and associated nonsheared broken cloud fields are up to $25\%$ of the albedo: sheared clouds reflect more when shearing is away from the sun and reflect less, by a comparable amount, when shearing is toward the sun. In an azimuthally averaged, climatological sense, therefore, differences between the albedos of sheared and nonsheared clouds are small. Ideally, a field of realistic clouds should be used to elucidate the importance of shearing on radiation fields. This would then account for distributions of cloud sizes, thicknesses, shapes, and slant angles.

The essence of cloud field albedo $\alpha_c$ variability as a function of $\varphi_0$, be it for sheared or nonsheared clouds, rests primarily on the concept of effective cloud fraction $A_c$ presented to the direct solar beam and on individual cloud albedo $\alpha_c$. For a given cloud field and solar zenith angle, changes in $\alpha_c$ are approximated by

$$
\frac{d\alpha_c}{d\varphi_0} = \frac{\partial A_c}{\partial \varphi_0} \frac{dA_c}{d\varphi_0} + \frac{\partial \alpha_c}{\partial A_c} \frac{dA_c}{d\varphi_0}.
$$

Since the partial derivatives are positive, the sign of (4) is governed by how $A_c$ and $\alpha_c$ change with $\varphi_0$. Note that changes in $\alpha_c$ due to cloud–cloud interactions are accounted for in $\alpha_c$, which changes with intercloud spacing. Figures 2, 3, and 5 demonstrate that while $dA_c/d\varphi_0$ and $d\alpha_c/d\varphi_0$ oppose each other, $dA_c/d\varphi_0$ is largely of the same sign and form as $dA_c/d\varphi_0$, which implies that cloud field albedo is governed most by $A_c$. This
reiterates the importance of implementing climate models with some means of estimating \( A_r \) (cf. Welch and Wielicki 1985; Kobayashi 1988).

Using both the idealized and the model-generated clouds, it was shown that cloud and cloud field bidirectional reflectance functions (BDRFs) can be sensitive to solar azimuth angle relative to the cloud shearing direction. In fact, differences in BDRFs for the same idealized cloud field but for \( \phi_0 = 0^\circ \) and \( 180^\circ \) can be as large as 50% for viewing zenith angles used frequently for data analyses. Some consolation was obtained, however, in that BDRF differences as a function of \( \phi_0 \) for the more realistic clouds are approximately half those for the idealized clouds. Nevertheless, uncertainties of this magnitude in BDRFs as a function of \( \phi_0 \) could have important ramifications for remote inference of cloud properties, most notably albedo and optical depth.

Fig. 15. BDRFs in the principal plane for the Mie and Heyney–Greenstein cases referred to in Fig. 14. Realistic clouds were used at \( t = 42, 45, \) and 49 min (see Fig. 6). Solid lines are for \( \theta_0 = 0^\circ \), long–short dashed lines are for \( \theta_0 = 30^\circ \), and dashed lines are for \( \theta_0 = 60^\circ \).
It was demonstrated that BDRFs associated with sheared clouds may rarely be equal to 1.0 at viewing angles near 60°. Unfortunately, this differs from non-sheared broken clouds (Davies 1984) and, therefore, makes it difficult to support the claim that viewing zenith angles near 60° offer least biased estimates for inference of cloud field albedo. However, BDRFs measured perpendicular to cloud shearing direction are almost independent of $\varphi_0$ provided shearing is close to, toward, or away from the sun.

Finally, differences in BDRFs arising from assuming either Mie or Henyey–Greenstein scattering phase functions are, as expected, most pronounced in the vicinity of direct backscatter (the opposition effect). The magnitude of BDRF differences arising from these disparate assumptions about the microphysical scattering nature of clouds is typically less than 25% of the magnitude of the BDRF differences due to whether clouds are sheared toward or away from the sun.

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