A Three-Dimensional Radiative Transfer Model to Investigate the Solar Radiation within a Cloudy Atmosphere. Part II: Spectral Effects

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(Manuscript received 16 January 1997, in final form 21 January 1998)

ABSTRACT

In this second part of a two-part paper, the spectral response of the interaction between gases, cloud droplets, and solar radiation is investigated using a Monte Carlo-based three-dimensional (3D) radiative transfer model with a spectral resolution of 0.005 μm. Spectrally resolved albedo at the top of the atmosphere, transmission to the surface, and absorption throughout the atmospheric column between 0.25 and 4.0 μm are computed and compared for 3D and independent pixel approximations at various solar zenith angles.

Analysis of a tropical cloud field shows that for overhead sun, the effects of cloud morphology reduce absorption in the UV and increase absorption in the water-vapor absorption bands. At steep solar zenith angles, the enhanced absorption shifts spectrally to the near-infrared atmospheric windows, where increases up to 50% in absorption by cloud droplets are obtained. While there is no change in absorption in the visible, the 3D effect is shown to produce false estimates of cloudy-column absorption based on residual net fluxes in this spectral region. Alterations to the albedo and enhanced absorption in the 3D computations generate reduced estimates in remotely sensed cloud optical thickness and overestimates in cloud-droplet size distribution. Finally, a band ratio of 0.94 to 1.53 μm downwelling irradiance at the surface is proposed as a possible measure of 3D enhanced atmospheric absorption.

1. Introduction

In Part I of this paper (O’Hirok and Gautier 1998, henceforth referred to as OG98), we described the various spatial mechanisms by which cloud morphology can impact the shortwave radiative field. Examination of a tropical cloud field showed that the assumption of plane-parallel clouds leads to underestimates in broadband shortwave atmospheric absorption in the presence of clouds, increased transmission to the surface, and a reduction in top of the atmosphere (TOA) albedo. An original motivation for this research was to determine if 3D cloud effects could account for the 25–30 W m⁻² discrepancy between theoretical estimates and recent observations of atmospheric absorption in the presence of clouds as reported by Cess et al. (1995), Ramanathan et al. (1995), and Pilewskie and Valero (1995). Although we found that the 3D cloud effect alone could not account for the magnitude of enhanced absorption, we will show in this second paper that it may explain some of the difficulties associated with assessing cloudy-column absorption.

Part of the debate on enhanced cloud absorption centers on the reliability of broadband absorption estimates based on residuals of net fluxes from measurements gathered within a spatially complex environment. Spectral measurements of albedo and reflectance that are easier to perform, suggest that the discrepancy between theory and observation is much smaller than recently reported by Cess and others (Stephens and Tsay 1990), or that the enhanced absorption may merely be an artifact of the performed analysis (Imre et al. 1996). However, as the word spectral implies, such measurements cannot provide direct broadband absorption, but can only be used to infer absorption based on a combination of theoretical models and measurements in selected spectral bands. Hence, conclusions about absorption depend, to a degree, on the very models that are being deliberated upon. In this paper, we examine the spectral distribution of the 3D radiative field and investigate if and how the plane-parallel assumption can bias conclusions made about cloudy-column absorption derived from spectral measurements. Furthermore, we discuss how measurements could be used to evaluate the importance of 3D effects.

2. Background

Clouds primarily scatter incident radiation in the ultraviolet and visible (<0.7 μm) and both scatter and
Fig. 1. Spectral transmission to the surface for all gases (dark gray) and water vapor (light gray). Overlay of cloud-droplet single-scattering albedo for effective radii of 4, 8, and 16 μm.

absorb in the near- and middle infrared (0.7–4 μm). The amount of energy absorbed within a cloud depends on the cloud droplet microphysics (i.e., single scattering albedo, phase function, and extinction coefficient), the density of cloud particles and their spatial distribution, interstitial aerosol and gas properties, and the spectral disposition of the impinging radiation. All optical properties vary spectrally. For cloud droplets, the single-scattering albedo is a function of wavelength, droplet size, and the complex index of refraction. The spectral variation of the single-scattering albedo is generally coherent with the spectral variations of the extinction coefficient of water vapor (Fig. 1). Exploiting this theoretical knowledge, cloud spectroscopy techniques have been established to infer cloud properties from remote sensing. Based on results from remote sensing, enhanced cloud absorption has been raised as an issue but dismissed as relatively insignificant (Stephens 1996).

The ratio of the near-infrared albedo to the visible albedo of a cloud field provides a direct indication of potential problems in the numerical modeling of absorption by clouds. It is generally assumed that the albedo in the visible portion of the shortwave spectrum is well understood and that discrepancies occur in the near-infrared. For a stratus layer, Hayasaka et al. (1995) obtained ratios of near-infrared albedo to visible albedo ranging from 0.67 to 0.81 that are inconsistent with model results showing values near 0.85. For the more homogeneous clouds encountered in their observations, it is possible to model the observed albedo in the visible and near-infrared with a single cloud-droplet distribution. However, for the more heterogeneous clouds, no single cloud-droplet distribution can account for the albedo simultaneously observed in both spectral regions. Similar findings were obtained by Hignett (1987), who presented observations of near-infrared albedo lower than results from plane-parallel radiative transfer models. While these results suggest an “anomaly,” the near-infrared to visible albedo ratio has been employed by Stephens (1996) to demonstrate the difficulties in reconciling the reported 25–30 W m⁻² discrepancy. Based on model computations, Stephens shows that the near-infrared to visible albedo ratio would need to drop by 50% to a level below 0.5 for the 25–30 W m⁻² reported enhanced absorption. To date, however, the value of 0.5 for the near-infrared to visible albedo ratio is inconsistent with reported observations.

Based on spectral reflectance, the assumption that the enhanced absorption is water related, and thus occurs in the near-infrared, is not unreasonable. Stephens and Platt (1987) demonstrated that theory overestimates near-infrared reflectance predominantly in atmospheric window regions and only slightly underestimates reflectance near the visible at 0.75 μm. At 2.25 μm, Twomey and Cocks (1982) demonstrated that to match remotely sensed droplet size distributions with in situ cloud physics measurements, a three- to five-fold increase in the absorption coefficients is required. Nakajima and King (1991) showed comparable results with in situ measurements being 2–5 μm less than effective radii estimated from 2.16-μm reflectance data. To match the predicted drop size with the measured size, an anomalous water-vapor absorption correction term needed to be entered into the calculation. Stephens (1996) suggest that for a plane-parallel cloud, a 50% reduction in near-infrared reflectance at 2.16 μm is equivalent to an in-
crease in droplet effective radius from 10 to 50 \( \mu m \). Again, analogous to the albedo ratio, such droplet sizes are inconsistent with observations for stratus clouds. Partially due to spatial sampling issues, most comparisons between observations and theory are limited to layered clouds—either solid stratus or less homogeneous stratocumulus. For these clouds, the plane-parallel assumption is not unreasonable. However, the new results of Ramanathan et al. (1995), Pilewskie and Valero (1995), and to some extent Cess et al. (1995) are based on tropical clouds, for which this assumption is suspect. To place an upper bound to potential 3D effects and to evaluate the problems associated with the plane-parallel assumption within the context of these more recent studies, all the 3D and 1D radiative computations are performed for a tropical cloud field.

3. Method

The atmospheric radiative transfer model used in this study is based on the Monte Carlo method. This technique and other 3D radiative transfer methods used in similar investigations has been extensively described in OG98. The model includes all major atmospheric gases and aerosols. Cloud microphysical properties are based on calculations derived from Mie scattering theory while gaseous absorption is computed using the \( k \)-distribution method from LOWTRAN 7 (Kneizys et al. 1988). Complete Monte Carlo computations are performed for the entire solar spectrum (0.25–4.00 \( \mu m \)) at 0.005- \( \mu m \) resolution. Comparisons with a discrete-ordinate radiative transfer model (Ricchiazzi et al. 1998) for clear sky and various plane-parallel clouds demonstrates that there is good agreement both spectrally and broadband (OG98).

The model spatial environment consists of a synthesized cloud scene embedded within a typical tropical atmosphere partitioned into 47 layers. From the surface to 10 km the thickness of the layer is 400 m becoming progressively thicker with altitude above that height. Horizontally, it is partitioned into 800 m \( \times \) 800 m cells arranged on an 80 \( \times \) 50 grid. Cloud geometry is synthesized from cloud-top heights derived from satellite imagery (Fig. 2). Cloud-base altitude of the convective cells is fixed at 1200 m with a maximum cloud thickness of 8800 m. Clouds that are difficult to detect from satellite imagery because of pixel resolution or multiple-cloud layering have been included to more closely resemble an actual cloud field. Numerous small cumulus congestus clouds with a maximum areal extent of 1600 m and cloud thickness of 1200 m are added near the base of the large convective cells. Scattered altostratus cloud layers 800–1200 m thick at a base altitude of 6000 m were also included, their total areal coverage being approximately 12%.

Internally, along the horizontal plane, the liquid water content (LWC) and effective radius (\( r_e \)) remain constant within the modeled clouds. Vertically, LWC varies with the slope of the adiabatic curve. The effective radius also varies vertically and ranges from 4.2 \( \mu m \) near the base of the convective cells to 16 \( \mu m \) at 2400 m above the cloud base and held constant to the cloud top. For the cumulus congestus clouds, \( r_e \) ranges from 4.4–10 \( \mu m \), and for altostratus clouds, 5.5–8.0 \( \mu m \). The mean effective radius of the field is 11.7 \( \mu m \). For the entire field the maximum optical thickness is 220, with a mean of 92.

Model computations are performed in a 3D mode (3DM) and independent pixel mode (IPM). The IPM essentially performs a plane-parallel computation at each grid cell. Photons are confined in the horizontal direction and are allowed vertical travel only through the atmospheric column. The 3DM more closely simulates the flow of radiation through the atmosphere by...
Fig. 3. Spectral ratio of 3DM to IPM model results for (a) TOA albedo and (b) transmission to surface at solar zenith angles of 0°, 30°, and 60°. Beneath each plot is 3DM model results for TOA albedo and transmission to the surface expressed as a fraction of TOA insolation.

4. Spectral results

To examine the 3D effect on normalized measured quantities, such as spectral albedo or transmission, the ratio of the 3DM to IPM results are presented in Fig. 3. As a reference, the 3DM albedo and transmission are shown in the lower portion of each panel. The quantities are averages for the entire spatial domain. Gaps in the plots represent points where either the IPM or 3DM results are at, or close enough to zero, that the significance of the ratio is lost in the noise introduced by Monte Carlo computations.

For the TOA albedo, the 3DM is smaller at all wavelengths and for all sun angles. Within the visible, and extending into the near-infrared, the albedo ratio remains constant and ranges between 0.95 and 0.98. The highest value occurs at 60° since the direct beam intercepts not only the top of the cloud, but the sides as well, effectively increasing the areal coverage of the 3D cloud field (Fig. 4a). For the IPM, which treats clouds as having a zero aspect ratio, the direct beam cannot intercept allowing both vertical and horizontal photon travel. For both modes, the actual distribution of atmospheric properties is precisely the same, and thus differences in the results can be directly attributed to the plane-parallel assumption.

From Part I (OG98), the 3D results showed a 7% reduction in albedo, an 18 W m⁻² increase in surface downwelling irradiance, and a 12 W m⁻² increase in total atmospheric absorption for broadband solar radiation (0.25–4.00 μm). These values represent daylight means for the entire spatial domain of the model. At solar noon, peak differences occur for the upwelling and downwelling fluxes, but interestingly, the peak absorption takes place at a 45° solar zenith angle. For various manifestations of the tropical cloud field expressed as a single-layered homogeneous cloud (more typical of the representations used in climate models), the difference from the 3D computations ranges from −16 to 38 W m⁻².

Fig. 4. (a) Schematic of the flow of radiation along the direct beam for a steep solar zenith angle as it intercepts the top and side of a cloud in the 3DM computations. (b) Flow of radiation for the IPM computations where the direct beam intercepts the cloud top or surface only.
the side of a cloud, and the exposure to the direct beam does not change with solar zenith angle (Fig. 4b). Beyond approximately 1.2 \( \mu \text{m} \), however, proportionally more of the radiation intercepted by cloud sides becomes absorbed rather than scattered. The net effect is a change in the solar zenith angle of maximum albedo from 60\(^\circ\) to 0\(^\circ\) above a pivot point near 1.2 \( \mu \text{m} \). At wavelengths where the cloud-droplet single-scattering albedo is relatively low, the effects on the TOA albedo can be dramatic. At 1.53 \( \mu \text{m} \), the albedo is reduced by 15\% to 25\% depending on the solar zenith angle. At 1.98 \( \mu \text{m} \), the reduction is from 25\% to 40\%. And for wavelengths greater than 3.4 \( \mu \text{m} \), the reduction approaches 50\% for a solar angle of 60\(^\circ\).

The transmission of solar radiation to the surface is also subject to 3D effects. For overhead sun, the 3DM transmission is enhanced by as much as 20\%. Spectrally, the variation is relatively constant with the lowest values occurring beyond 3.4 \( \mu \text{m} \). At 30\(^\circ\), the transmission is also higher from the ultraviolet wavelengths to 2.0 \( \mu \text{m} \). Beyond this wavelength, however, the transmission for the 3DM drops by as much as 20\% near 3.4 \( \mu \text{m} \). For the 60\(^\circ\) solar zenith angle, the transmission is greater by 5\%–10\% in the ultraviolet and visible, but dramatically falls off in the near-infrared with attenuation at the surface as high as 20\% to 40\% for the wavelengths of 1.65 and 2.25 \( \mu \text{m} \), respectively. This reduction in transmission is directly attributable to increases in absorption by cloud droplets.

To examine the spectral nature of 3D-enhanced absorption in the atmosphere, the absorption of solar radiation has been integrated along the horizontal plane of the model domain and plotted as a function of altitude. In Fig. 5, the upper panel represents absorption obtained from the 3DM computations, whereas the lower shows the difference between the 3DM and IPM for solar zenith angles of 4° (Fig. 5c) and 60° (Fig. 5d). The dashed lines define the vertical boundaries of the cloud field. It should be noted that within upper reaches of the cloud field, most of the cells are void of clouds. Overall, 9\% of the field is completely clear of clouds. Accordingly, there may be some transmission to the surface at wavelengths that are normally opaque to an overcast sky.

Readily apparent for both solar zenith angles (Figs.
of the cloud, but also the side, effectively increasing the areal coverage of the cloud (Fig. 4a). For spectral regions with substantial absorption, the downwelling enhancement is further reduced as cloud leakage is dampened. For the IPM, as noted previously, the direct beam cannot intercept the side of a cloud, and thus comparing the two modes, the IPM now allows a larger transmission of energy to the lower portions of the atmosphere where it can be absorbed by water vapor.

As the single-scattering albedo generally decreases further into the near-infrared at 1.38, 1.87, and 2.7 \( \mu m \), the task of discerning the separate effects of water vapor and cloud droplets becomes more formidable. At solar noon, absorption is maximized in the upper portion of the cloud field to the extent that little radiation is transmitted below 4 km. At 60°, the longer pathlength raises this cutoff level by a kilometer. Since virtually all the radiation is absorbed in the upper reaches of the cloud field, differences between the 3DM and IPM are negligible. The continuous features appearing between the absorption bands are caused by cloud droplets.

For both solar zenith angles of 0° and 60°, greater absorption by the 3DM is caused by a combination of water vapor and cloud droplets. Naturally, the highest absorption levels (75 mW m\(^{-3}\) \( \mu m \)^{-1} at 0°) arise wherever the cloud is exposed to the direct solar beam. For this cloud field, a large proportion of the cloud tops are above 8 km. The altostratus cloud layer located at an altitude of 6 km is responsible for intense line spread across the spectrum from 1.0 to 4.0 \( \mu m \). Generally, enough energy is available in the near-infrared spectral regions between the atmospheric windows for absorption to occur in all cloud layers between 1 and 10 km. However, for wavelengths greater than 3.0 \( \mu m \), the low solar input and strong absorption properties of cloud droplets prevents the transmission of radiation below the altostratus cloud layer.

Most of the 3D-enhanced cloud-droplet absorption takes place within the spectral ranges of 1.15–1.30 and 1.5–1.8 \( \mu m \) with minor absorption effects between 0.95–1.05 and 2.0–2.4 \( \mu m \). At solar noon, the 3DM has greater absorption in the lower half of the cloud field with maximum increases over the IPM ranging between 2 and 4 mW m\(^{-3}\) \( \mu m \)^{-1}. Most of this increase is caused by energy being focused into these regions by leakage from clouds at higher altitudes. This leakage out of the clouds, however, actually causes the IPM to produce slightly more absorption at these higher altitudes. But the effect is gradually dampened as the wavelength increases. At 60°, the 3D enhanced absorption is shifted toward the upper half of the cloud field with maximum values reaching 5 mW m\(^{-3}\) \( \mu m \)^{-1}. Here, 3D computations allow for the impinging solar beam to strike the cloud side at a higher angle than the IPM. The result is for some photons to travel farther into the cloud where they can become “trapped” and eventually absorbed.

By additionally integrating the absorption along the vertical axis, the spectral dichotomy responsible for the
3D peak enhancement that occurs between 30° and 60° becomes clearer. Figure 6 shows the atmospheric absorption partitioned between gases and cloud droplets. For overhead sun, the lower albedo of the 3DM reduces absorption in the ultraviolet by 8 W m\(^{-2}\) \(\mu\)m\(^{-1}\), but this loss is insignificant compared to the enhancement from absorption by water vapor in the near-infrared. Within the 0.94-\(\mu\)m water-vapor band, increases of 30 W m\(^{-2}\) \(\mu\)m\(^{-1}\) are observed. For steeper sun angles, the absorption enhancement caused by gases is reduced. However, it is partially compensated by increases in absorption by cloud droplets. At 60°, the 3DM enhancement reaches 50% at 1.24 and 1.62 \(\mu\)m.

Spectrally integrated, the net compensation is not a zero sum since much of the enhancement by gases and droplets occurs within different spectral regions. Below 1.2 \(\mu\)m, for example, the enhancement due to water-vapor absorption is reduced as the solar zenith angle increases. This reduction is not caused by greater absorption from cloud droplets, but merely is the response to an increase in 3D albedo. Further into the near-infrared, a large amount of the enhanced absorption by
cloud droplets occurs within the atmospheric window and has no direct effect on absorption by gases. But as the sun progresses toward the horizon, some of the enhanced absorption by cloud droplets occurs along the edges of the water vapor bands causing a decrease in absorption by water vapor.

5. 3D effects on measurements

a. Residual absorption

The measurement of atmospheric absorption cannot be made directly, but estimated only through the residual of the differences of broadband net fluxes or inferred from spectral measurements of albedo, transmission, or both. All methods, to a degree, are impacted by the spatial characteristics of the cloud fields. An example of the spatial problems inherent in using the residual of the differences of net fluxes is demonstrated in Fig. 7 for atmospheric-column absorption between 400 m and 11 km and between 15 and 20 km. At each of these altitudes, the net flux (downwelling − upwelling) as a fraction of the TOA insolation is computed. To highlight the difficulties associated with the residual method, computations are made at 0.42 μm where conservative scattering is dominant. The only absorption occurring at this wavelength is by oceanic aerosol, for which the maximum total atmospheric column absorption is less than 0.5% of the TOA insolation. Hence, any values above this level or those that are negative may be considered as an estimate of the error associated with this specific cloud morphology. The fluxes for this field are based on runs of 40 000 000 photons.
For the residual method to be applicable, the assumption must be made that energy flows vertically and that horizontal fluxes can be neglected. Since the IPM is based on this assumption, the absorption inferred from the net flux agrees with the actual absorption computations. However, for the 3DM, horizontal diffusion dramatically alters absorption estimates. At 11 km, the net flux appears diffused with the darkest patches emanating from the highest cloud tops where much of the downwelling irradiance is reflected back toward space. The brightest areas are represented by columns that are void of clouds. Although the values approach 50% of the TOA insolation, the maximum would be much greater if photons were not scattered into these columns from adjacent cloudy cells. At 400 m, the diffusion is less pronounced since the variation in the distance between this layer and the cloud base is much smaller than it is between the 11-km layer and the cloud tops. Peak values near 1.2 occur for clear columns where the direct beam solar radiation is supplemented by the downward leakage of radiation from adjacent cloudy cells.

By subtracting the net flux at 400 m from the net flux at 11 km, the absorption is obtained. Since the actual maximum absorption is less than 0.5% of the TOA insolation, it is obvious that for the horizontal scale of individual columns (800 m × 800 m) the use of the residual of the differences of net fluxes for determining absorption is impossible. As shown, the absorption ranges from a positive 20% to a negative 80% in the clear columns. This pseudo-production of energy in clear sky comes at the expense of radiation diffused out of the clouds. On a larger spatial scale of 20 km × 20 km for an entirely cloudy column (outlined box), an absorption of 7% is still indicated. Taken over the entire spatial domain the absorption is only 0.2% since the model employs cyclic boundaries to maintain continuity of fluxes.

Even for layers completely void of clouds, the effects of an underlying cloud field on the estimate of absorption can be significant. Comparing the net fluxes at 15 and 20 km, it is clear that the degree of diffusion occurring in a given layer depends on the distance between that layer and the scattering location of the radiation. Thus, in the presence of clouds in the atmosphere, no two different vertical layers can share the same radiation pattern. This assured spatial incoherence produces absorption estimates up to 10% for atmospheric layers between 15 and 20 km where nominally the absorption is nil. The results presented here represent a rather extreme case, and for less complex cloud fields and through prudent spatial and temporal averaging, the errors associated with estimating absorption based on the residual of the differences of net fluxes can presumably be reduced.

b. Near-infrared to visible albedo ratio

As proposed by Stephens (1996), the near-infrared to visible albedo ratio provides a criterion on the effects clouds have on the absorption of solar radiation. Direct measures of this ratio for layered clouds range between 0.68 and 0.95 (Hayasaka et al. 1995; Stephens 1996). In Table 1, the visible and near-infrared albedo, the albedo ratio, and the atmospheric absorption are listed for the 3DM and IPM computations. Additionally, results from three plane-parallel tropical cloud parameterizations are included. As explained in Part I, it is not possible to produce exact plane-parallel equivalents to the 3D cloud field. Thus, different parameterizations used are: ISCCP (Fig. 9b in Rossow and Schiffer 1991), Stephens-Cb (Stephens 1978), and a plane-parallel cloud using the mean cloud-base altitude, geometric thickness, effective radius, and liquid water content of the 3D cloud field (Type II). The results from each cloud representation are combined with those for the 9% clear sky. The outcomes listed in the table represent quantities averaged over daylight hours.

As shown in Table I, all of the ratios for the near-infrared to visible albedo fall within the limits of observations. The 3DM and IPM albedo results are relatively close at 0.74 and 0.77, respectively. Without the slight compensatory effect of a lower visible albedo for the 3DM, the difference between the two would be 0.06 rather than 0.03. Since the 3D-enhanced absorption represents much less than half the values recently reported, the ratio is not expected to approach the 0.5 ratio suggested by Stephens (1996) as the maximum level capable of reproducing these findings. However, a comparison between the plane-parallel results for the Stephens-Cb and ISCCP representation reveals an intriguing element of Stephens (1996) assertion.

Both of these clouds represent large convective cells,

<table>
<thead>
<tr>
<th>Cloud type</th>
<th>Visible</th>
<th>Near-infrared albedo</th>
<th>NIR/Vis ratio</th>
<th>Atmospheric absorption (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3DM</td>
<td>0.71</td>
<td>0.52</td>
<td>0.74</td>
<td>214</td>
</tr>
<tr>
<td>IPM</td>
<td>0.73</td>
<td>0.56</td>
<td>0.77</td>
<td>202</td>
</tr>
<tr>
<td>Type II</td>
<td>0.77</td>
<td>0.63</td>
<td>0.83</td>
<td>200</td>
</tr>
<tr>
<td>ISCCP</td>
<td>0.74</td>
<td>0.67</td>
<td>0.89</td>
<td>176</td>
</tr>
<tr>
<td>Stephens-Cb</td>
<td>0.81</td>
<td>0.59</td>
<td>0.72</td>
<td>230</td>
</tr>
<tr>
<td>max - min</td>
<td>0.10</td>
<td>0.15</td>
<td>0.17</td>
<td>54</td>
</tr>
</tbody>
</table>
Fig. 8. (a) Inferred mean optical thickness of cloud field from the matching of plane-parallel computations of 0.62-µm TOA albedo to that of IPM (light gray) and 3DM (dark gray) model results. Effective radius of plane-parallel cloud is held constant at 11.7 µm. Inferred mean effective radius of cloud field from the matching of plane-parallel computations of (b) 2.13-µm TOA albedo to that of IPM (light gray) and 3DM (dark gray) model results. Optical thickness of plane-parallel cloud is held constant at τ = 102. Results are shown for solar zenith angles of 0°, 30°, and 60°.

but because the Stephens-Cb ($r_e = 32$ µm) has larger cloud droplets than the ISCCP ($r_e = 10$ µm), it absorbs 54 W m⁻² more solar radiation (daylight average). Although this difference in absorption is near the level of the discrepancy between model computations and observations recently suggested, the ratio for the Stephens-Cb is 0.72: only 0.17 less than that for ISCCP. Thus, it becomes clear that not all plane-parallel clouds are equal, and that the means by which clouds are represented may account for part of the discrepancy between measurement and theory.

c. Inferred cloud microphysical properties

As noted in the background, part of the impetus behind the issue of enhanced absorption arose from the difficulty in reconciling in situ measurements of cloud microphysical properties from those inferred from reflectance data. To examine the issue further, the simulated spectral albedo from the IPM and 3DM computations are compared to those from a plane-parallel cloud model (Type II) to infer cloud microphysical properties. In reality, such methods would employ reflectance at a spatial resolution higher than that used in this exercise, but the results should provide a gauge on the upper bounds of the error associated with the plane-parallel assumption for retrieving cloud microphysical properties.

To estimate cloud optical thickness, the liquid water content of the plane-parallel cloud is adjusted until the albedo at 0.62 µm matches that computed from either the IPM or 3DM. As shown in Fig. 8a, the use of the plane-parallel assumption can have a dramatic effect on the retrieval of cloud optical thickness for a morphologically complex cloud field. From Table 1, the difference between the plane-parallel and either the IPM or 3DM computations represent less than a 10% reduction in the visible albedo. Due primarily to the nonlinear relationship between bulk radiative properties and optical thickness, however, the estimated optical thickness value retrieved is approximately one-half that of the actual optical thickness of the cloud field, τ = 102. In addition, the inferred optical thickness increases with solar zenith angle. This tendency agrees with the results of Loeb and Davies (1996), who found a systematic bias with solar zenith angle using a plane-parallel model to
retrieve cloud optical thickness from Earth Radiation Budget Experiment satellite observations.

To estimate cloud-effective radius, the same technique is used, but the wavelength is changed to the near-infrared, and the effective radius of the plane-parallel cloud is varied while the optical thickness is held constant. At 2.13 μm, the effective radius inferred from the IPM albedo is virtually identical to the mean effective radius (11.7 μm) of the 3D cloud field (Fig. 8b). This finding is rather surprising, considering that the effective radius of cloud droplets in the cloud tops within this field varies between 4.4 and 16 μm. Based on the 3DM albedo at 2.13 μm, the estimated effective radius is 17 μm at solar zenith angles of 0° and 30° and reaches 23 μm at 60°. It is not the nonlinear relationship between bulk radiative properties and optical thickness that is important here. Rather, the 3D enhancement of absorption by cloud droplets produces the discrepancy between inferred and actual cloud microphysical properties.

d. Enhanced absorption

As demonstrated in model simulations, the effect of cloud morphology on the radiative field varies spectrally and according to the angle of the sun. For high solar angles, cloud morphology produces an increase in absorption in the spectral regions of gaseous absorption and to a smaller degree, enhances absorption by cloud droplets within the near-infrared atmospheric windows. As the sun approaches the horizon, the absorption by cloud droplets increases and encroaches upon the water-vapor absorption bands to the point where a reduction in absorption by water vapor occurs at several wavelengths. As shown in Fig. 9a, the 0.94 to 1.53 μm absorption ratio shows a strong divergence between the IPM and 3DM fluxes with increasing solar zenith angle. When related to the angle of the sun, this spectral absorption differential provides an observable spectral signature in atmospheric transmission (Fig. 9b) and albedo (Fig. 9c) ratios. These ratios can serve as an indication of the 3D effect, but they should be convolved with an estimate of the cloud field optical thickness, as a signal of the same magnitude could theoretically be produced by variations in the optical properties of a plane-parallel cloud over time.

6. Conclusions

For the cloud field used in this investigation, it is shown that cloud morphology reduces absorption in the UV and increases absorption in the gaseous absorption bands for overhead sun. At steeper solar zenith angles, the enhanced absorption spectrally shifts to the near-infrared atmospheric windows, where increases up to 50% in absorption by cloud droplets are obtained. While there is no change in absorption in the visible, the 3D effect is shown to produce false estimates of cloudy column absorption based on residual net fluxes in this spectral region. Therefore, it is not unreasonable to assume that part of the cloud absorption “anomaly” may be tied to the issue of spatial sampling. Although this problem is not unknown, the approaches taken to minimize this effect are debatable. Additionally, as demonstrated, spectral measurements of cloud albedo, which are considered to be more reliable, are not immune to cloud heterogeneity. Hence, to understand the radiative effects of clouds, broadband and spectral, it is essential to have an appreciation of the interdependent nature of cloud microphysical and macrophysical properties. The convoluted interaction between processes occurring at these two extremely different scales provides a partial explanation for the differences found between theory and observation of atmospheric absorption in the presence of clouds and for the related discrepancies between remotely sensed estimates of cloud microphysical properties and in situ measurements.

Acknowledgments. We are grateful to Dr. Paul Ricchiazzi for his valuable insight and assistance with implementation of the LOWTRAN-7 routines. This research has been funded in part by Department of Energy Grants 90ER61062 and 90ER61986, National Science Foundation Grant ATM-9319483, and National Aeronautics and Space Administration Grant NAGW-31380.

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