INVESTIGATION OF A VISIBLE REFLECTANCE PARAMETERIZATION FOR DETERMINING CLOUD PROPERTIES IN MULTI-LAYERED CLOUDS

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1. INTRODUCTION

The techniques employed to routinely derive cloud properties from satellite data for ARM and the Clouds and the Earth's Radiant Energy System (CERES) use parameterizations of cloud reflectance and effective emittance determining the optical depth and effective particle size of clouds. These retrievals typically assume that the cloud in a given pixel is a single-layered plane-parallel cloud. Because overlapped clouds are common, this assumption often results in cloud properties that represent some mixture of the multi-layered cloud properties and do not provide an accurate assessment of actual cloud properties in the scene. Various methods using combinations of infrared and solar channels (Baum et al. 2000) and solar and microwave data (Lin et al. 1999) have been developed to detect multi-layered clouds. Once identified, it is necessary to unscramble the properties for each of the cloud layers. If it is assumed that the properties of the lower layer cloud are known, it should be possible to derive the properties of the upper-level cloud from either infrared or visible data. This paper investigates the potential for deriving the upper-cloud optical depth and effective particle size of clouds. These retrievals typically assume that the properties of the lower layer cloud are assumed to be single-layered plane-parallel. Because overlapped clouds are common, this assumption often results in cloud properties that represent some mixture of the multi-layered cloud properties and do not provide an accurate assessment of actual cloud properties in the scene. Various methods using combinations of infrared and solar channels (Baum et al. 2000) and solar and microwave data (Lin et al. 1999) have been developed to detect multi-layered clouds. Once identified, it is necessary to unscramble the properties for each of the cloud layers. If it is assumed that the properties of the lower layer cloud are known, it should be possible to derive the properties of the upper-level cloud from either infrared or visible data. This paper investigates the potential for deriving the upper-cloud optical depth and effective particle size of clouds.

2. VISIBLE REFLECTANCE PARAMETERIZATION

A new parameterization was developed to improve the accuracy of the estimated top-of-atmosphere (TOA) reflectances for clouds over dark and bright surfaces compared to those from a detailed adding-doubling (AD) radiative transfer model (RTM; see Minnis et al. 1993). This parameterization is based on the AD equations using the same lookup tables developed as in Minnis et al. (1998) that include the diffuse cloud albedo \( \alpha_{cd}(\tau, r) \), cloud albedo \( \alpha_c(\tau, r, \theta_c, \phi) \), and the cloud reflectance \( \rho(\tau, r, \theta_c, \theta, \phi) \), where \( \tau \) and \( r \) are the cloud optical depth and effective particle size, respectively. The solar and viewing zenith and relative azimuth angles are \( \theta_c \), \( \theta \), and \( \phi \), respectively. The parameterization also uses the lookup tables of atmospheric reflectance \( \rho_o(\tau_o, \theta_o, \theta, \phi) \), albedo \( \alpha_o(\tau_o, \theta_o) \), and diffuse albedo \( \alpha_{cd}(\tau_o, \theta_o) \) due to Rayleigh scattering (Minnis et al. 1993). The parameterization assumes the atmosphere is divided into three layers with a lower surface. The top layer, designated layer 1, and layer 3 are Rayleigh scattering layers, while layer 2 is the cloud layer.

The reflectance for two adjacent layers is computed using the adding equations. The combined reflectance for the top Rayleigh layer and the cloud layer is

\[
R_{12} = \rho_{11} + \alpha_c' D_1 (1 - \alpha_{cd1}) + t_{11}(\mu) [t_{11}(\mu_o) \rho_o + S_1] \tag{1}
\]

where

\[
\alpha_c' = \alpha_c t_{11}(\mu_o) + [1 - t_{11}(\mu_o)] \alpha_{cd1}
\]

\[
D_1 = T_1 (1 + S_1)
\]

\[
S_1 = \alpha_{cd1} / (1 - \alpha_{cd1})
\]

\[
T_1 = 1 - t_{11}(\mu_o) - \alpha_{cd1} t_{11}(\mu_o)
\]

\[\mu, \mu_o = \cos \theta, \cos \theta_o\]

\[t_{11} \text{ is the direct Rayleigh transmission as defined by Minnis et al. (1993), and the numeric indices refer to a layer or combination of layers. The downward transmittance of the two layers is} \]

\[
T_{12} = D_1 [T_2 + t_2(\mu)] + T_2 t_{11}(\mu_o)
\]

where

\[T_2 = 1 - \alpha_c' t_2(\mu_o)\]

and \( t_2 \) is the direct transmittance of the cloud (Minnis et al. 1993).

The combined reflectance for the three layers is

\[
R_{123} = R_{12} + \alpha_{cd2} D_2 T_{12}' + (\rho_{12} t_2(\mu) t_{12}(\mu_o) + S_2) t_2(\mu) t_{11}(\mu_o)
\]

where

\[D_2 = T_2 (1 + S_2)\]

\[S_2 = Q_2 / (1 - Q_2)\]

\[Q_2 = \alpha_{cd2} R_{12}'\]

\[R_{12}' = \alpha_{cd1} (1 - \alpha_{cd1}) + t_{11}(\mu_o) \alpha_{cd1} t_{11}(\mu_o) + S_1\]

\[T_{12}' = U_1' (1 + S_1)\]

and

\[U_1' = (1 - \alpha_{cd1}) (1 + S_1)\]

The downward transmittance for the three layers is

\[
T_{123} = D_2 [T_3 + t_3(\mu)] + T_2 t_{11}(\mu_o)
\]

where

\[T_3 = 1 - \alpha_{cd2} t_3(\mu_o)\]

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The combined atmosphere and surface reflectance is

\[ R_{\text{TOA}} = (R_{\text{sa}} + \Delta R) \exp(-\tau_{\text{gas}}(1/\mu + 1/\mu_s)). \]  

(6)

The exponential term accounts for gaseous absorption and, in practice, varies with the altitude of the cloud.

When used for retrievals, the values of \( \Delta R \) are computed for the specified values of \( \alpha_{\text{ad}}, \rho_s, \tau \) by linear interpolation and extrapolation between the values used to create the coefficients for (5). Equation (6) was tested for a wider range of various cloud models, surface albedos, and cloud pressures. The resulting relative differences between (6) and the AD calculations for those cases plus the original cases used in the formulation are summarized in Table 1 under the heading, “new parameterization.” Results from the old parameterization from Minnis et al. (1993) are also shown to demonstrate the increase in accuracy and precision over the full range of surface albedo. The largest instantaneous errors occur for extreme values of \( \theta \), while the largest average errors for a given parameter occur for \( \tau < 0.1 \). For example, the greatest average difference for a given \( \phi \) in the low albedo range is 0.9% for \( \tau = 0.5 \) at \( \phi = 180^\circ \). Thus, if the AD TOA reflectance \( \rho_{\text{TOA}} \) is 6% \( \phi = 180^\circ \), the average value from (6) is 6.06%. Overall, the differences are comparable to those between a high-resolution AD model and a discrete ordinates RTM (Y. Hu, personal communication 2001).

Because of its high accuracy for large surface albedos, (6) may be useful for simulating multilayered cloud reflectances in the following manner. The optical depth of the low-level cloud is first estimated in some independent manner such as the application of a microwave method (Lin et al. 1999) or by direct retrieval using nearby pixels without upper-level cloud contamination. The combination of the reflectances from the low-level cloud and the surface can be assumed to be a new surface and the terms \( \alpha_{\text{ad}} \) and \( \rho_s \) are replaced in the parameterization by the new diffuse albedo and reflectance for the combined low-level cloud and surface layer.

This concept was tested by performing AD calculations for a range of conditions. The surface albedos are 0.04 and 0.20 with low-level clouds at \( \rho_c = 900 \text{ hPa} \), \( r_o = 10 \text{ µm} \), and \( \tau = 2 - 64 \). The upper-level cloud is specified at \( \rho_c = 250 \text{ hPa} \), \( D_o = 68 \text{ µm} \), and \( \tau = 0.25 - 8 \). A discrete set of angles was also specified: \( \theta = 15, 45^\circ \); \( \mu_s = 0.35, 0.75 \); and \( \phi = 5, 35, 90, 135, \) and 175°.

<table>
<thead>
<tr>
<th>( \alpha_{\text{ad}} ) (%)</th>
<th>new parameterization</th>
<th>old parameterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-10</td>
<td>-0.01 ± 0.53 %</td>
<td>-0.08 ± 5.1 %</td>
</tr>
<tr>
<td>10-50</td>
<td>-0.01 ± 0.67 %</td>
<td>-0.14 ± 7.0 %</td>
</tr>
<tr>
<td>50-90</td>
<td>0.03 ± 1.04 %</td>
<td>-4.3 ± 12.4 %</td>
</tr>
</tbody>
</table>
3. RESULTS

Figure 1 shows the variation of $\rho_{\text{TOA}}$ with the upper cloud optical depth $\tau_1$ over a low-level cloud with optical depth $\tau_2 = 2$ over a surface with albedo of 0.2. Each symbol corresponds to a different set of viewing angles. All of the reflectances increase monotonically with increasing $\tau_1$. For a given value of $\tau_1$, $\rho_{\text{TOA}}$ is generally greater for the larger value of $\theta$ and small $\phi = 90^\circ$. The reflectances are usually greater for the backscattering direction except for the near sun-glint set of angles ($41^\circ$, $45^\circ$, $5^\circ$). The relative variation of $\rho_{\text{TOA}}$ for the given angle sets when $\tau_2 = 16$ (Fig. 2) is similar to that in Fig. 1, except that the reflectance does not change monotonically with $\tau_1$ in all cases. It is nearly constant for small values of $\tau_1$ at certain viewing angles. For $\theta = 15^\circ$ and $\phi = 90^\circ$, $\rho_{\text{TOA}}$ actually decreases to a minimum at $\tau_1 = 1$ before increasing. This darkening of a scene by a thin over thick cloud can often be observed from the window of a commercial aircraft.

Preliminary results for the parameterization are shown in Fig. 3 for the same conditions used for Fig. 1. In this case, the parameterization yields the same monotonic variation but under- and overestimates $\rho_{\text{TOA}}$, especially for larger values of $\tau_1$. The behavior of $R_{\text{TOA}}$ in Fig. 4 for the same conditions used in Fig. 2 is certainly different from that in Fig. 3 and is non-monotonic in one case. However, the parameterization captures little of the decrease in $R_{\text{TOA}}$ for $\tau_1 < 2$. At some of the angles, the drop in $R_{\text{TOA}}$ is replaced by a significant increase in $R_{\text{TOA}}$. The model over- and underestimates the AD reflectances by up 0.02 in some cases. Fortunately, these results are some of the worst cases.
Table 2. Mean relative differences in % between new parameterization and AD TOA reflectances for overlapped clouds as function of angle.

<table>
<thead>
<tr>
<th>Angle</th>
<th>τ₂ = 0.5</th>
<th>1.0</th>
<th>2</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ₀ = 41°</td>
<td>2.1</td>
<td>2.5</td>
<td>1.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>θ₀ = 41°</td>
<td>-1.8</td>
<td>-2.3</td>
<td>-1.3</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>θ = 45°</td>
<td>2.9</td>
<td>3.5</td>
<td>2.7</td>
<td>1.6</td>
<td>0.8</td>
</tr>
<tr>
<td>θ = 45°</td>
<td>-2.1</td>
<td>-2.7</td>
<td>-2.2</td>
<td>-0.7</td>
<td>0.2</td>
</tr>
<tr>
<td>φ = 5°</td>
<td>-1.2</td>
<td>-1.1</td>
<td>-0.8</td>
<td>-0.3</td>
<td>-0.1</td>
</tr>
<tr>
<td>φ = 45°</td>
<td>-0.1</td>
<td>0.0</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>φ = 90°</td>
<td>1.1</td>
<td>1.1</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>φ = 135°</td>
<td>0.9</td>
<td>0.7</td>
<td>0.7</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>φ = 175°</td>
<td>0.3</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

A summary of the differences relative to the Ad results is given in Table 2 for αₛ = 0.2. The average differences depend on the viewing and illumination angles as well as τᵢ. The percent differences are smallest for larger values of τᵢ, a result that is not surprising given that the multiple scattering for the thin cloud over a bright surface is more difficult to model. The mean differences are less than 1.1% when averaged over all solar and viewing zenith angles for a given relative azimuth angle. However, larger mean errors result for constant values of θ or θ₀. Overall, the mean difference and its standard deviation for all of the cases considered here for αₛ = 0.2 is 0.001 ± 0.017, or 0.2% ± 3.0%. The differences are slightly larger for the lower-albedo surface: 0.002 ± 0.018 or 0.4% ± 3.2%.

The overall differences are substantially larger than those for the bright surfaces in Table 1. The latter were based on reflectance calculations that assumed that the underlying surface was a Lambertian reflector. The contributions of multiple scattering by the anisotropically reflecting lower cloud to the upwelling direct beam through the thin upper-level cloud may be different than the simple diffuse albedo term used in the formulation of (6). The new parameterization applied to multilayered clouds, however, produces more accurate results than those from the old parameterization for dark surfaces. However, for modeling multilayered clouds, an accuracy better than 3% would be desirable.

4. CONCLUDING REMARKS

Much additional research is required before drawing any firm conclusions about the utility of applying this approach to model reflectance fields from multilayered cloud systems. The results presented here can be considered as preliminary because alterations made in the code to utilize the cloud-surface calculations have not been thoroughly verified. Additionally, only a small set of angles and cirrus-stratus cloud combinations have been considered. A more thorough analysis using additional ice crystal effective diameters and a greater range of upper-level cloud optical depths will be used with other surface albedos and water droplet effective radii for the low-level cloud. Finally, the retrieval accuracy for upper level cloud optical depths will be examined by using this model to derive the optical depth from AD reflectance calculations.

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REFERENCES