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Investigation of the Effects of the Macrophysical and Microphysical Properties of Cirrus Clouds on the Retrieval of Optical Properties: Results for FIRE II

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Introduction

Due to the prevalence and persistence of cirrus cloudiness across the globe, cirrus clouds are believed to have an important effect on the climate. Stephens et al., (1990) among others have shown that the important factor determining how cirrus clouds modulate the climate is the balance between the albedo and emittance effect of the cloud systems. This factor was shown to depend in part upon the effective sizes of the cirrus cloud particles. Since effective sizes of cirrus cloud microphysical distributions are used as a basis of parameterizations in climate models, it is crucial that the relationships between effective sizes and radiative properties be clearly established. In this preliminary study, the retrieval of cirrus cloud effective sizes are examined using a two dimensional radiative transfer model for a cirrus cloud case sampled during FIRE Cirrus II. The purpose of this paper is to present preliminary results from the SHSG model demonstrating the sensitivity of the bispectral relationships of reflected radiances and thus the retrieval of effective sizes to phase function and dimensionality.

Two Dimensional Radiative Transfer Model

The Spherical Harmonic Spatial Grid (SHSG) method of radiative transfer developed by Evans (1993) is employed in this study. This method solves the two dimensional (2D) radiative transfer equation by approximating the radiance field in terms of a spherical harmonic expansion for the angular dependencies and a discrete grid for the spatial properties. The discretization of the radiative transfer equation in this way, along with the specified boundary conditions, results in a coupled linear system which is relatively sparse and is then solved iteratively using the conjugate gradient method. The advantage of SHSG for this study is that the transfer of radiation through arbitrary cloud inhomogeneities can be computed in an efficient manner. Additionally, since the radiance field at all grid points is expanded in terms of a spherical harmonic series, the radiances at any grid point or angle can be computed by summing over the truncated series. The summation of a truncated series introduces noise to the solution in the form of oscillations. In order to minimize these problems, the δ-M scaling method is used in order to damp the oscillations normally associated with truncating the Legendre series of the phase function and the Cesàro summation method (Dave and Armstrong, 1974) is adapted to two-dimensions to minimize the oscillations in the intensities. SHSG also has an independent pixel mode (I.P.) where the horizontal coupling of the radiation field is turned off, which simulates plane-parallel radiances. The 2D radiances produced from SHSG agree with Monte Carlo simulations to within 1% in the side scattering portion of the phase function, but can differ by at most 8% at the forward and backup scattering peaks. At this time the model is monochromatic and does not treat molecular scattering or absorption.

Estimation of the Cloud Field Optical Properties

For this study a 2D cloud field was obtained from a RHI scan by WPL's Ka-band radar for a cirrus cloud sampled on 26 November 1991 during the FIRE Cirrus II intensive field observation period (Taneil Uttal, personal communication). For the results shown here, an image was used which gave cloud reflectivities at 50 meter resolution and represented a rather homogeneous looking cirrus cloud characterized by a thick generating cell in the center. The cloud reflectivities were converted to ice water content using the empirical relation of Sassen (1987), $IWC = 0.037Z_i^{0.696}$, where Z_i is the reflectivity factor of ice ($mm^6 \cdot m^{-3}$) and IWC is the ice water content ($g \cdot m^{-3}$). The estimated ice water contents were then used to scale the extinctions computed from a modified gamma distribution of equivalent area spheres with IWC of 0.0216 $g \cdot m^{-3}$ and an effective radius of 80 μm. Table 1 gives the optical properties of the cloud simulated in this study. The extinctions were computed at the two Landsat wavelengths 0.83 and 1.65 μm. The single scatter albedos and phase functions were assumed to remain constant across the cloud domain but varied with wavelength. The single scatter albedos were computed with Mie theory and the phase functions were chosen to have asymmetry parameters consistent with the geometric optic computations of hexagonal ice crystals by Takano and Liou (1990 and personal communication). The asymmetry parameters for each wavelength were used as g_{eff} in the double Henyey-Greenstein function (DHG) to prescribe the phase function. The double HG has the form, $P(\cos\Theta) = b\ g_1 + (1-b)\ g_2$, where g_1, g_2 and b are constants related by $g_{eff} = b\ g_1 + (1-b)\ g_2$. Using the preceding assumptions, a cloud field was obtained which varied in extinction only, which means that the effective radius is held constant throughout the cloud.

Table 1: Cirrus cloud optical properties as a function of wavelength (λ) for the simulations presented in this paper.

λ (μm)	K_{ext} (km^{-1})	ω_0	b	g_1	g_2	g_{eff}
0.83	0.45863	0.9998	1.000	0.790	-0.600	0.79
			0.970	0.833	-0.600	0.79
			0.920	0.911	-0.600	0.79
1.65	0.46264	0.8940	1.000	0.810	-0.550	0.81
			0.970	0.852	-0.550	0.81
			0.920	0.928	-0.550	0.81

Results

Normalized nadir reflectances given by $R_\lambda = \frac{\pi L_\lambda}{\mu_0 F_{0_\lambda}}$ (Weilicki et al., 1990) were computed for the cloud fields described above using a grid of 110x29 which represented an area of approximately 11 km by 3 km. The solar zenith angle was 50°. The results are shown in the bispectral plot of reflectances at 0.83 and 1.65 μm as shown in Figure 1. For comparison, a series constant effective radius curves from 15 μm to 150 μm computed using the phase function with $b = 1$ (DHG1) and the independent pixel approximation of SHSG are plotted along with data in Fig. 1. As expected, the independent pixel results in the top panels of Fig. 1 give relationships which agree with the shapes of the effective radius curves and the reflectances from DHG1 lie on the 80 μm curve. However, it is also seen that the other forms of the phase function give reflectances that give underestimations of effective radii up to 35% for $\theta_0 = 50^0$ and over 80% for $\theta_0 = 10^0$. These underestimations decrease with increasing optical depth (optical depth increases from the origin along the curves). The sensitivity to the shape of the phase function is discussed by Wielicki *et al.* and is due to the magnitude of the phase function at a particular scattering geometry. In this case, the bispectral relationships at $\theta_0 = 10^0$ are much more sensitive than at $\theta_0 = 50^0$ because the forms of the phase function differed much more greatly in the backscatter portion ($\Theta = 170^0$) than in the sidescattered portion ($\Theta = 130^0$) of the phase function. The decreased sensitivity to the phase function shape as a function of optical depth is shown more clearly by Figure 2 which depicts the retrieved effective radius as a function of horizontal position throughout the cloud. The solid line gives the ideal retrieval for these cases since a distribution of 80 μm was assumed throughout the cloud. Referring to the I.P. retrieval lines shows that as optical depth increases the difference between the curves using DHG1 and DHG2 decreases dramatically. This sensitivity to the phase function in thinner clouds is due to the single scattering processes which dominate. As the cloud becomes thicker multiple scattering becomes more important and the individual shapes of the phase function become less important to the retrieval of effective radius.

Figure 1 also shows that unlike the independent pixel clouds, the 2D radiances for the upper cluster of points do not correspond in slope with the curves of effective radius. In fact, the thinner clouds give overestimations of effective radius up to a factor of 2 while the thicker clouds give underestimates of effective radius of 10-25% for $\theta_0 = 50^0$. The effect of the cloud geometry for this case is to change the fundamental relationship between the effective radii and the reflectances at the wavelengths shown for this preliminary study. This geometry effect can be better understood by referring again to Fig. 2. Note when comparing the 2D retrieval curves with the I.P. curves that the differences become greatest for the largest optical depth. Referring to the 3rd panel from the top and comparing it to the column optical depth in the bottom panel shows that at the front of the thickest part of the cloud (i.e., 4.5 km) there are underestimations of the effective radius while behind the cloud there are overestimations. This effect may be thought of as an "optical depth" shadowing phenomena because for this sun angle (50^0 where the sun comes from the left) radiances are enhanced in front of the cloud and decreased behind the cloud relative to the I.P. calculations. Note that for the higher sun angle shown in Fig. 1, this geometric effect is greatly reduced.

Lastly, figure 2 shows a large disagreement between the I.P. and curves and the ideal 80 μm line for the thinner clouds. This is due to the effects of the vertical inhomogeneities. Although this effect is not entirely understood at this time, it is clear that for thin clouds, as pictured in the top two panels of Fig. 2, the variation of optical along the vertical has a distinct effect on the reflected radiances as compared to an homogeneous cloud with an identical integrated optical depth. In cirrus which are dominated by thin clouds this process may play an extremely important role in the interpretation of the radiance fields.

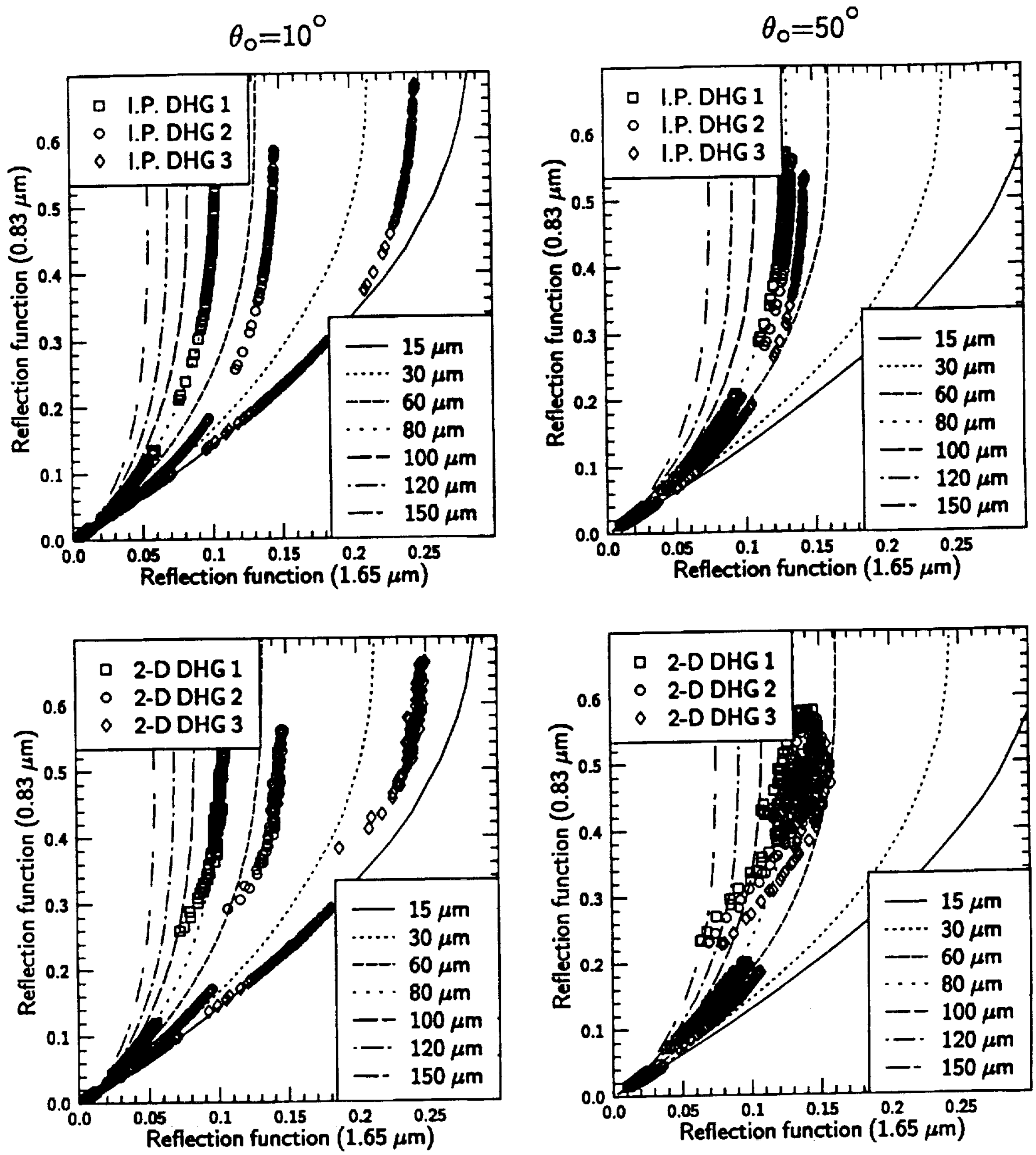

Figure 1: Bispectral plots of nadir reflectances for a simulated 2-D cirrus cloud field with variable exinction but constant effective radius ($r_e = 80\mu m$) with the optical properties shown in Table 1. The viewing angle is 0.0° and $\phi_o = 180°$. The top panels give I.P. results and the bottom panels give 2-D results. The solar zenith angle is labeled for each column.

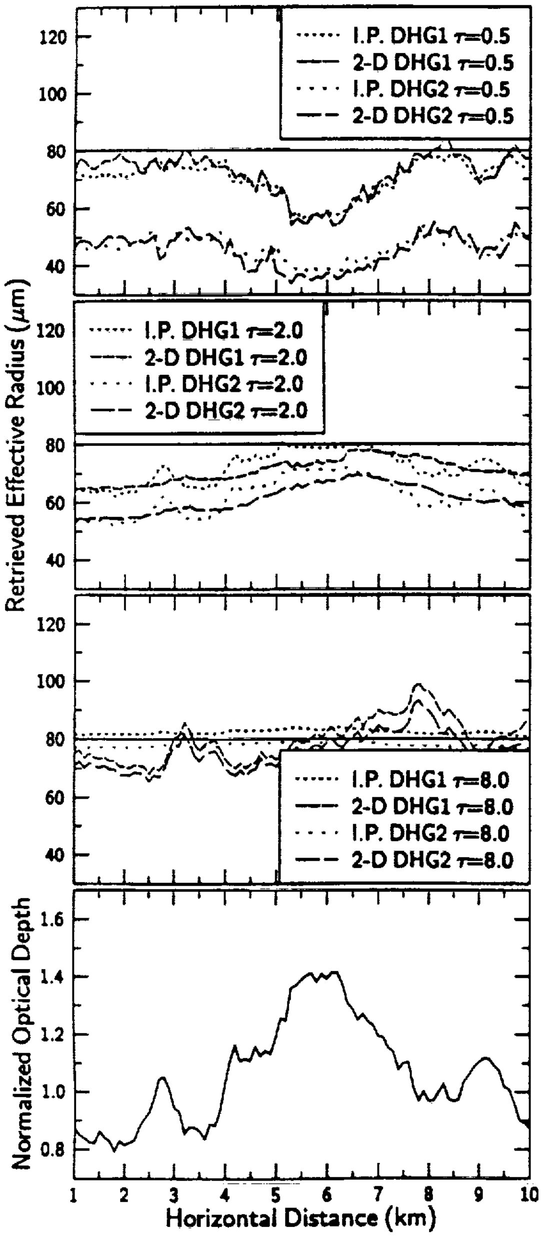

Figure 2: Retrieved effective radius as a function of horizontal position for the solar geometry of $\theta_o = 50.0°$, $\phi_o = 0.0°$ and a viewing angle of 0.0°. The top three panels represent 3 different optical depths and the bottom panel gives the integrated normalized optical depth throughout the cloud.

Conclusions

These results illustrate that retrieved cirrus effective radii contains significant biases not only due to the lack of understanding of ice scattering properties but also due to the inhomogeneities of the clouds systems. For cirrus clouds, which tend to be thinner, the sensitivities of the radiance fields to the shape of the phase function and to the vertical distribution of the optical depth may contribute greatly to biases in the retrieval of effective radius. Geometric biases may also play a role in very thick cirrus systems which sometimes occur in the tropics. Cirrus parameterizations based upon such retrieved effective radii will also produce biases in the radiative properties which may be important to the interpretation of climate simulations. This study shows that spectral changes in the radiance fields of cirrus clouds depend not only on the intrinsic microphysical properties of the clouds but also upon their spatial structure.

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