Sensitivity of Satellite-Retrieved Cloud Properties to the Effective Variance of Cloud Droplet Size Distribution

R.F. Arduini
Science Applications International Corporation
Hampton, Virginia

P. Minnis and W.L. Smith, Jr.
National Aeronautics and Space Administration Langley Research Center
Hampton, Virginia

J.K. Ayers and M.M. Khaiyer
Analytical Services and Materials, Inc.

P. Heck
Coorperative Institute for Mesoscale Meteorological Studies/
University of Wisconsin-Madison
Madison, Wisconsin

Introduction

Cloud reflectance models currently used in cloud property retrievals from satellites have been developed using size distributions defined by a set of fixed effective radii with a fixed effective variance. The satellite retrievals used for the Atmospheric Radiation Measurement (ARM) Program assume droplet size distributions with an effective variance value of 0.10 (Minnis et al. 1998); the International Satellite Cloud Climatology Project uses 0.15 (Rossow and Schiffer 1999); and the Moderate Resolution Imaging Spectroradiometer (MODIS) team uses 0.13 (Nakajima and King 1990). These distributions are not necessarily representative of the actual sizes present in the clouds being observed. Because the assumed distributions can affect the reflectance patterns and near-infrared absorption, even for the same droplet effective radius r_{eff}, it is desirable to use the optimal size distributions in satellite retrievals of cloud properties. Collocated observations of the same clouds from different geostationary satellites, at different viewing angles, indicate that the current models may not be optimal (Ayers et al. 2005). Similarly, hour-to-hour variations in effective radius and optical depth reveal an unexplained dependence on scattering angle. To explore this issue, this paper examines the sensitivity of the cloud reflectance at 0.65 and 3.90-µm to changes in the effective variance, or the spectral dispersion, of the modeled size distributions. The effects on the scattering phase functions and on the cloud reflectances are presented, as well as some resultant effects on the retrieved cloud properties.

Cloud Particle Size Distribution

The size distribution for the clouds modeled here is the modified Gamma distribution defined by Hansen (1971) and given by the following

$$n(r) = \text{constant } r^{(1-3b)/b} e^{-[r/(ab)]} . \tag{1}$$

It can be shown that the parameters defining this distribution are r_{eff} and the mean effective variance, v_{eff}

$$\begin{aligned} a &= r_{eff} \\ b &= v_{eff} \end{aligned} \tag{2}$$

given by

$$r_{eff} = \frac{\int_0^\infty r^3 n(r) dr}{\int_0^\infty r^2 n(r) dr} \tag{3}$$

and

$$v_{eff} = \frac{\int_0^\infty (r - r_{eff})^2 r^2 n(r) dr}{r_{eff} \int_0^\infty r^2 n(r) dr} . \tag{4}$$

For this investigation, the constant in the relation defining the distribution is not necessary since the cloud reflectance models employed in the retrievals require only normalized quantities.

Figure 1a shows the normalized number densities for a given effective radius value for a range of effective variances. The effect of increasing the effective variance is to shift the peak of the distribution toward smaller values, increasing the relative number of small particles, as well as increasing the overall width of the distribution, adding larger droplets. In Figure 1b, the effective variance is held constant for a range of effective radii. As the effective radius increases the distribution becomes broader.

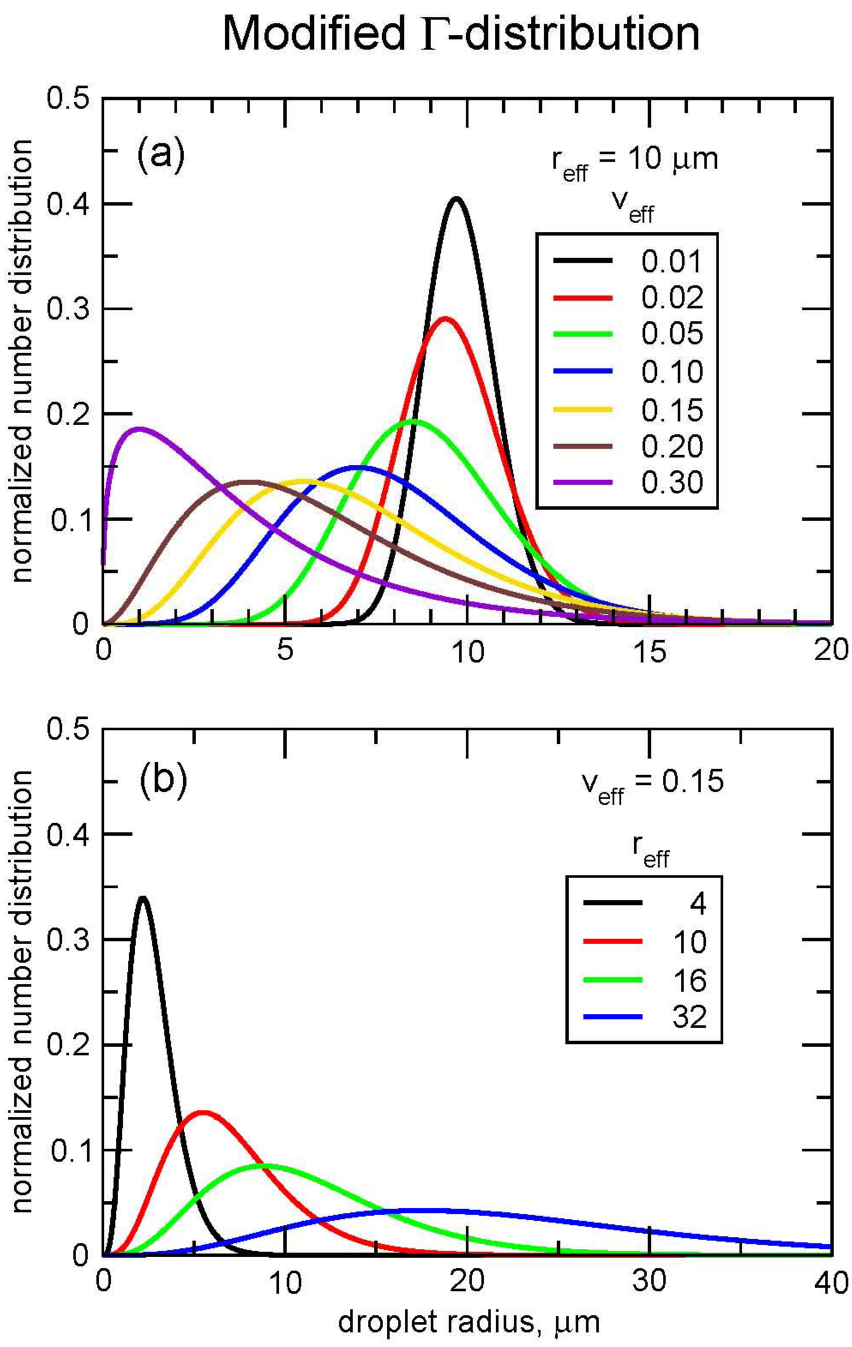

Figure 1. Normalized modified τ-distributions used in this study, showing (a) the effect of the parameter v_{eff} for a given r_{eff} and (b) the effect of r_{eff} for a given v_{eff}.

The spectral dispersion, d, is defined as the ratio of the standard deviation of the distribution to the mean value and, for the modified Gamma distribution, the spectral dispersion is related to the effective variance as follows:

$$d = \left(\frac{v_{eff}}{1 - 2v_{eff}} \right)^{1/2} . \tag{5}$$

Large variances are observed in stratus clouds and depend on air mass as found by Martin et al. (1994) using data taken near the Azores. They observed that there is an abundance of small particles in stratocumulus cloud layers, especially in those formed within continental air masses. They show spectral dispersions of about 0.3 for maritime air masses and 0.5 for continental. These correspond to effective variances of about 0.08 and 0.17, respectively. Politovich (1993) also notes that wide variations of dispersion do occur, especially near the tops and side edges of clouds where the dynamics of cloud turbulence dominate. Miles et al. (2000) have also found large variations in spectral dispersion in their database of stratus cloud size distribution parameters, with continental clouds showing dispersions of 0.8 (v_{eff} = 0.28) and larger.

Cloud Particle Scattering Phase Functions

The water droplets comprising the clouds are modeled as spheres and, as such, their optical properties are obtained using Mie scattering theory. The scattering phase functions at 0.65 and 3.90 µm for r_{eff} = 8 µm and v_{eff} ranging from 0.01 to 0.30 are shown in Figures 2 and 3. On the log scale, the phase functions appear to be very similar. To elucidate the sensitivity of reflectance to v_{eff}, these figures also show the differences in the phase functions resulting from changing v_{eff} from the value of 0.10 used in the ARM cloud retrievals from Geostationary Operational Environmental Satellites (GOES) data (Minnis et al. 2004). These differences are substantial, especially in scattering angle regions near the rainbow (~140° at 0.65 µm and 150°-165° at 3.9 µm) and glory angles (178°-180°), which are common in satellite viewing geometries. It is clear that using the wrong value of v_{eff} could produce an undulation in r_{eff} (from 3.9-µm radiances) and cloud optical depth τ (from 0.65-µm radiances) if the same cloud were viewed from gradually changing scattering angles.

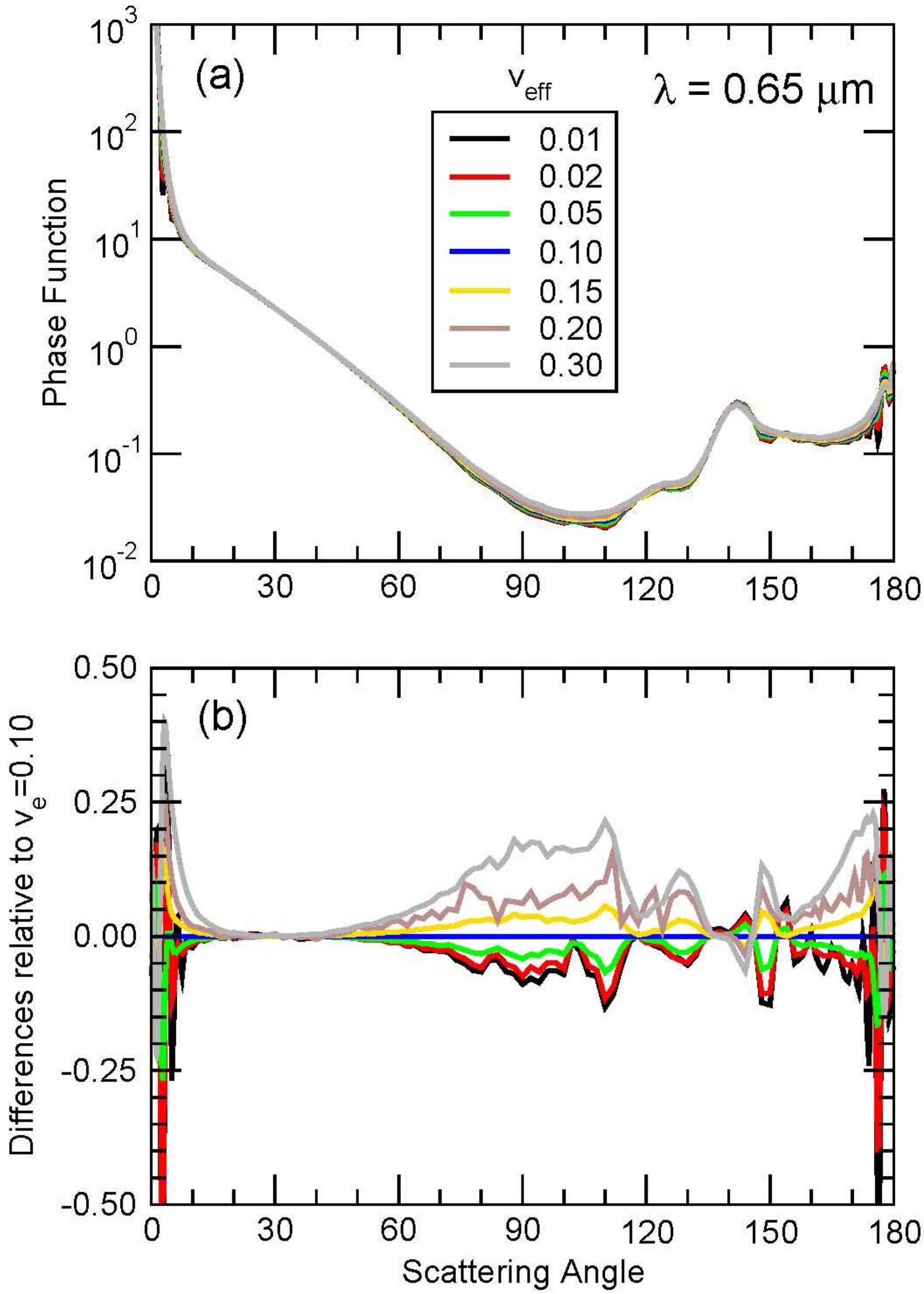

Figure 2. Scattering phase function for r_{eff} = 8 μm at 0.65 mm. (a) phase function and (b) differences in phase function due to v_{eff} relative to v_{eff} = 0.10.

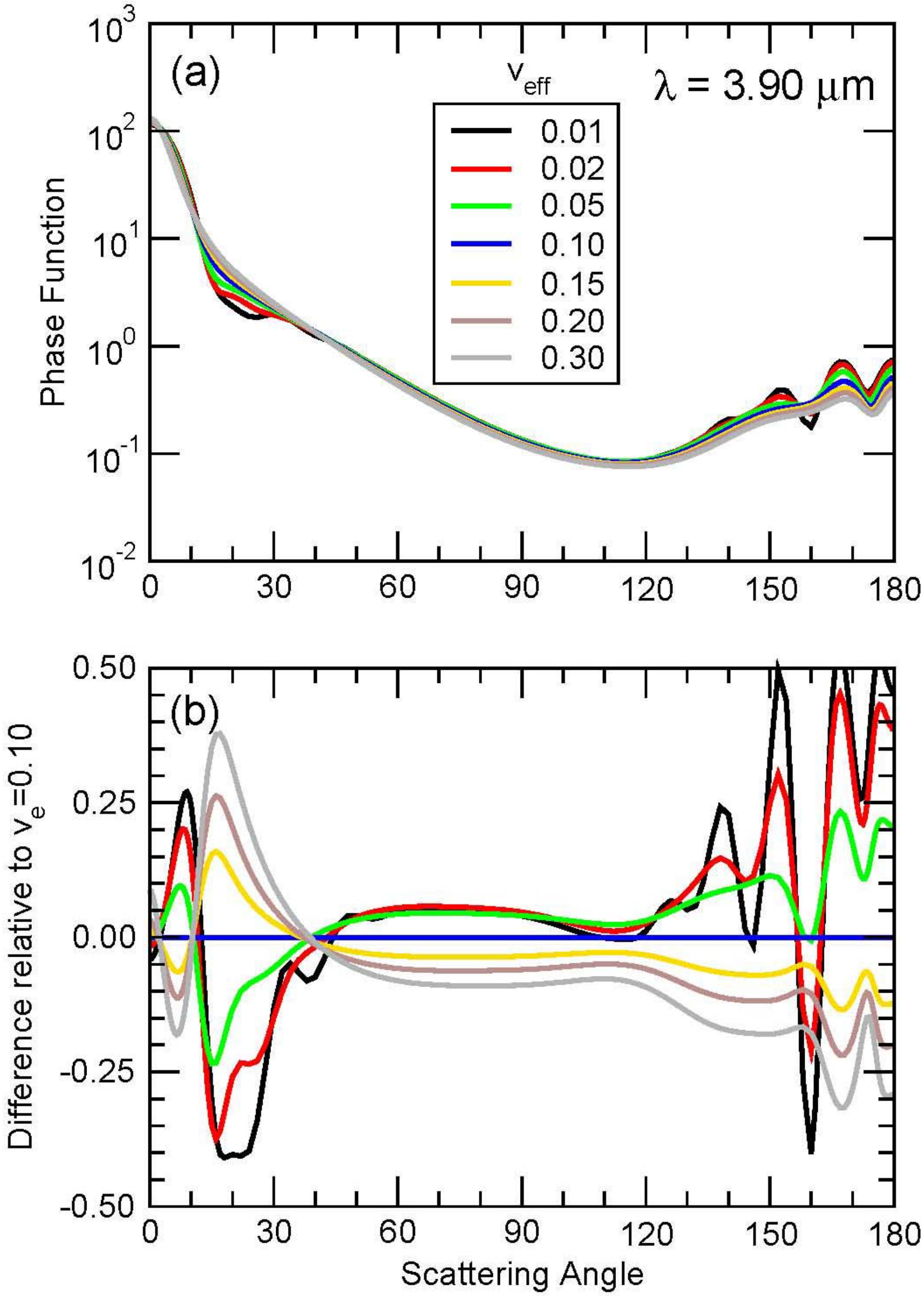

Figure 3. Same as Figure 2, except $\lambda = 3.90$ μm.

Figures 4 and 5 show how these phase function differences due to the variation in the width of the size distributions manifest themselves in the cloud reflectance. For a cloud of moderate visible optical thickness τ_{vis} = 1.0, the difference in the 0.65-μm reflectance from the current models is on the order of 10% in certain regions of the principal plane and can exceed 25% in the 3.9-μm reflectance. Thus, the impact of v_{eff} errors on retrieved r_{eff} are probably larger than those on τ. These differences are only slightly reduced for optically thick clouds.

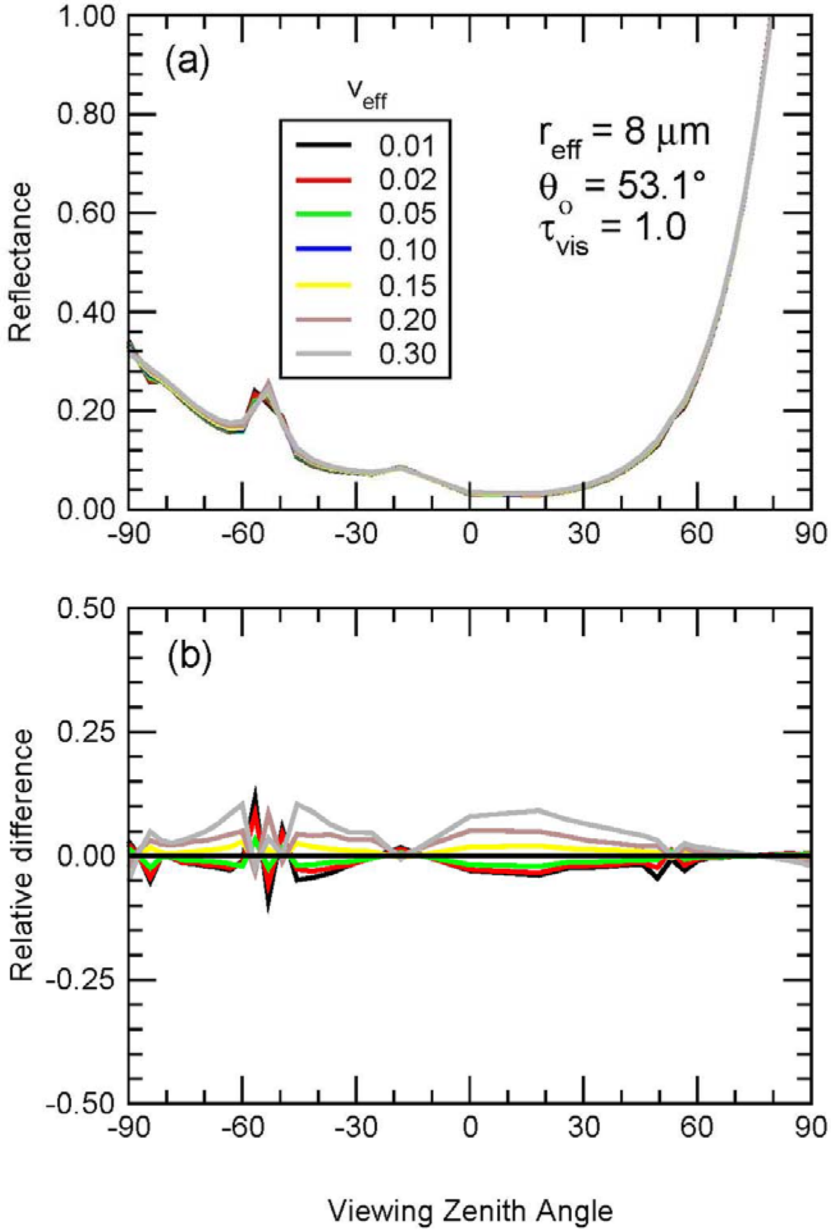

Figure 4. Cloud reflectance at 0.65 μm for a typical satellite observation. (a) reflectance in the principal plane and (b) relative difference with respect to v_{eff} = 0.10.

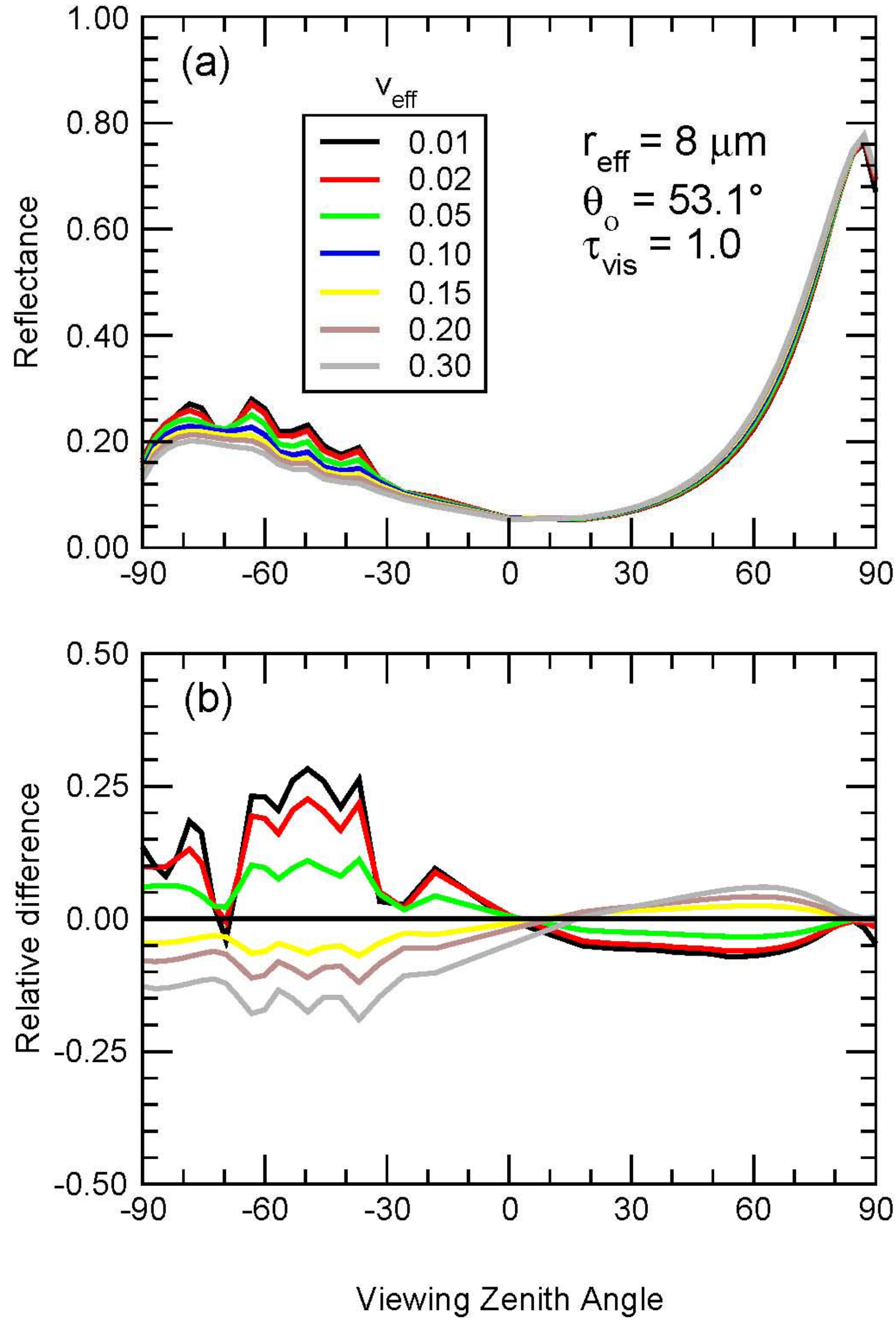

Figure 5. Same as Figure 4, except $\lambda = 3.90$ μm.

Retrieval Results

To further explore the effect of the sensitivity of the cloud reflectance to v_{eff}, cloud reflectance lookup tables were calculated using a range of values for v_{eff} following the procedures of Minnis et al. (1998). These new tables were then applied to simultaneous GOES-10 and GOES-12 observations of a cloudy region in the central United States where the satellite fields of view overlap. Figure 6 shows the impact on the retrieved value of the effective radius using both a smaller (v_{eff} = 0.05) and a larger (v_{eff} = 0.30) effective variance. The narrower distribution seems to have less of an effect on the retrieved size, while the broader distribution decreases the retrieved cloud droplet sizes.

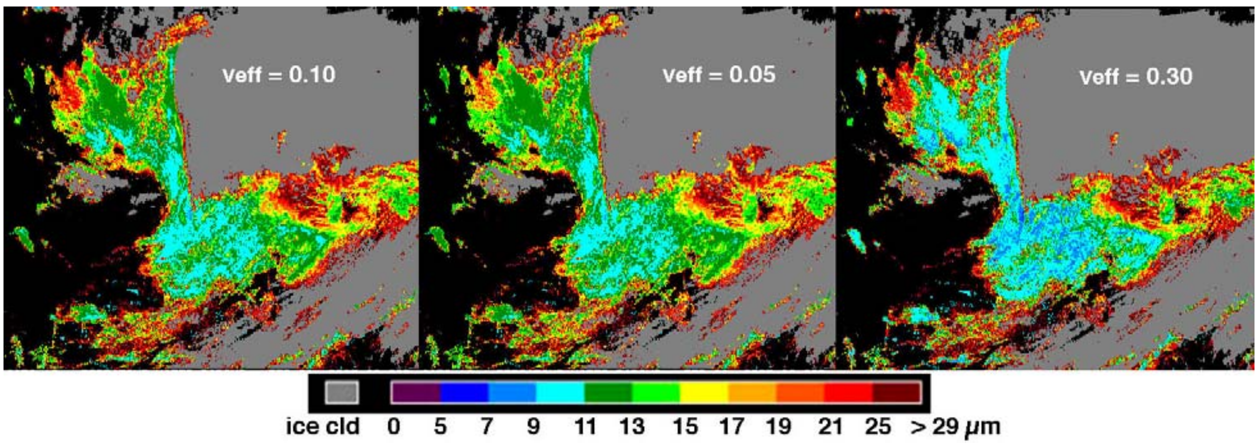

Figure 6. GOES-12 retrieval of effective radius using both smaller and larger values of v_{eff} in the models used in the retrieval algorithm.

Figures 7 and 8 show the scatterplots and linear correlations between retrievals of r_{eff} and τ from GOES-10 and GOES-12 for 2 hours each during 11 April and 19 October 2005, respectively, over the central United States. The hours, 1725 and 1975 UTC are on opposite sides of local noon so that the GOES-10 and -12 scattering angles (Θ) are reversed, to some extent, between those 2 hours. The statistics for each case are listed in Table 1 along with Θ. The correlations appear to improve with increased effective variance and the observed bias, probably due to the different scattering angles, is also reduced. For three of the times, the v_{eff} = 0.3 model produces the line closest to the line of agreement, but at 1975 UTC, 19 October (Figure 8c), the 0.2 variance model yields the better results. The linear fits to the r_{eff} data are somewhat divergent in Figure 7, but are more parallel in Figure 8. This change probably results from the differences in Θ. During April, the differences in the 3.9-µm phase function (Figure 3) between the 0.2 and 0.3 models and the 0.1 models are different at each pair of scattering angles (Table 1), while the differences at each pair of angles are nearly the same for the October cases. The large differences and poor correlations in Figure 8c, d do not appear to be the result of effective variance problems. Perhaps, the large numbers of supercooled cloud pixels used in this match are part of the problem. For example. roughly half of the pixels are supercooled with some clouds as cold as 250 K. The potential for mixed phase clouds is significant in those conditions and could substantially alter the average scattering phase function for the clouds. More comparisons are necessary before a definitive conclusion can be drawn, but these results indicate that it would be advantageous to allow for variations in the effective variance of distributions used in these retrievals.

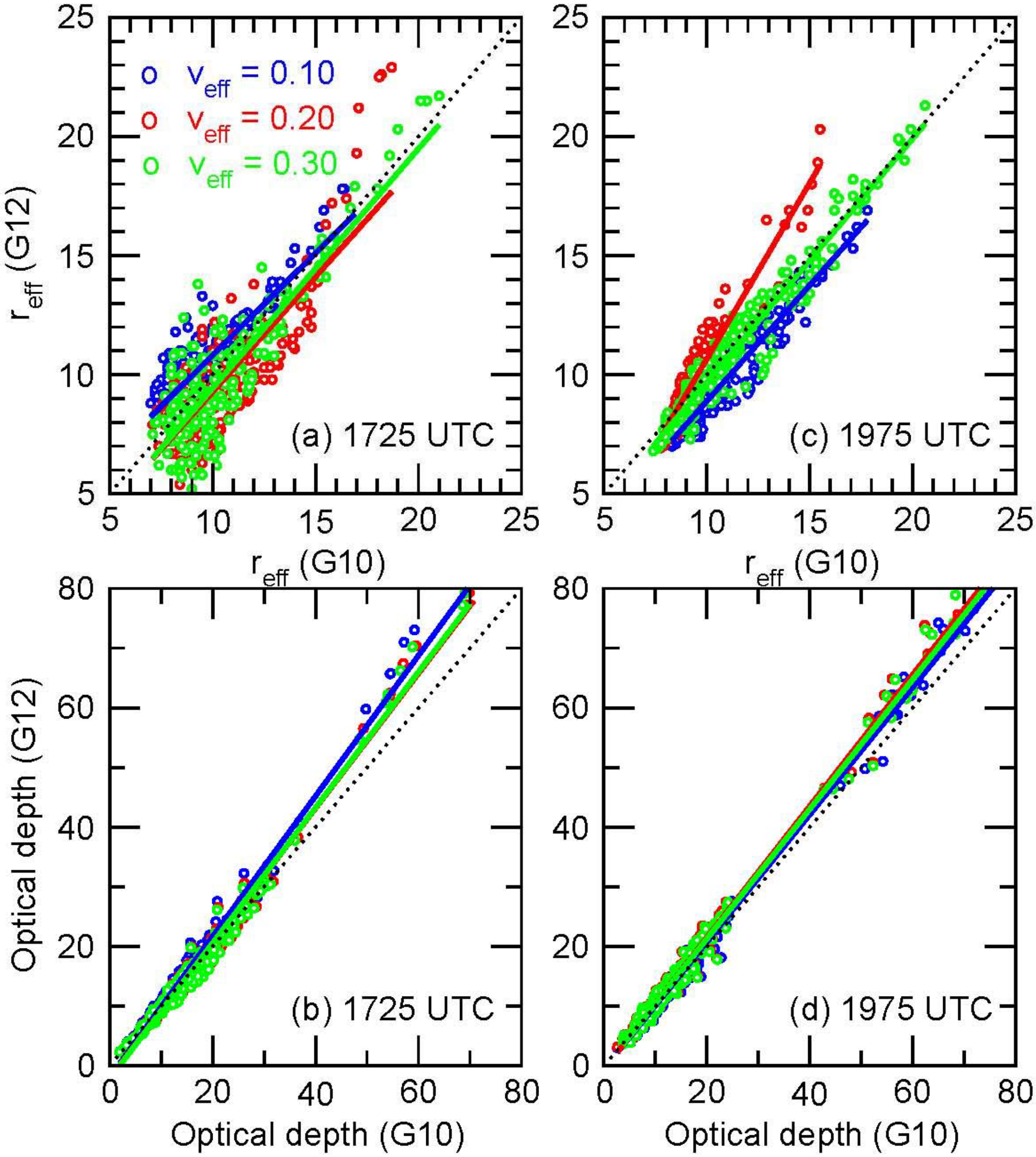

Figure 7. Correlation of retrievals of effective radius (a, c) and optical depth (b, d) from overlapped observations by GOES-10 and GOES-12 at two times on April 11. See Table 1 for correlation statistics.

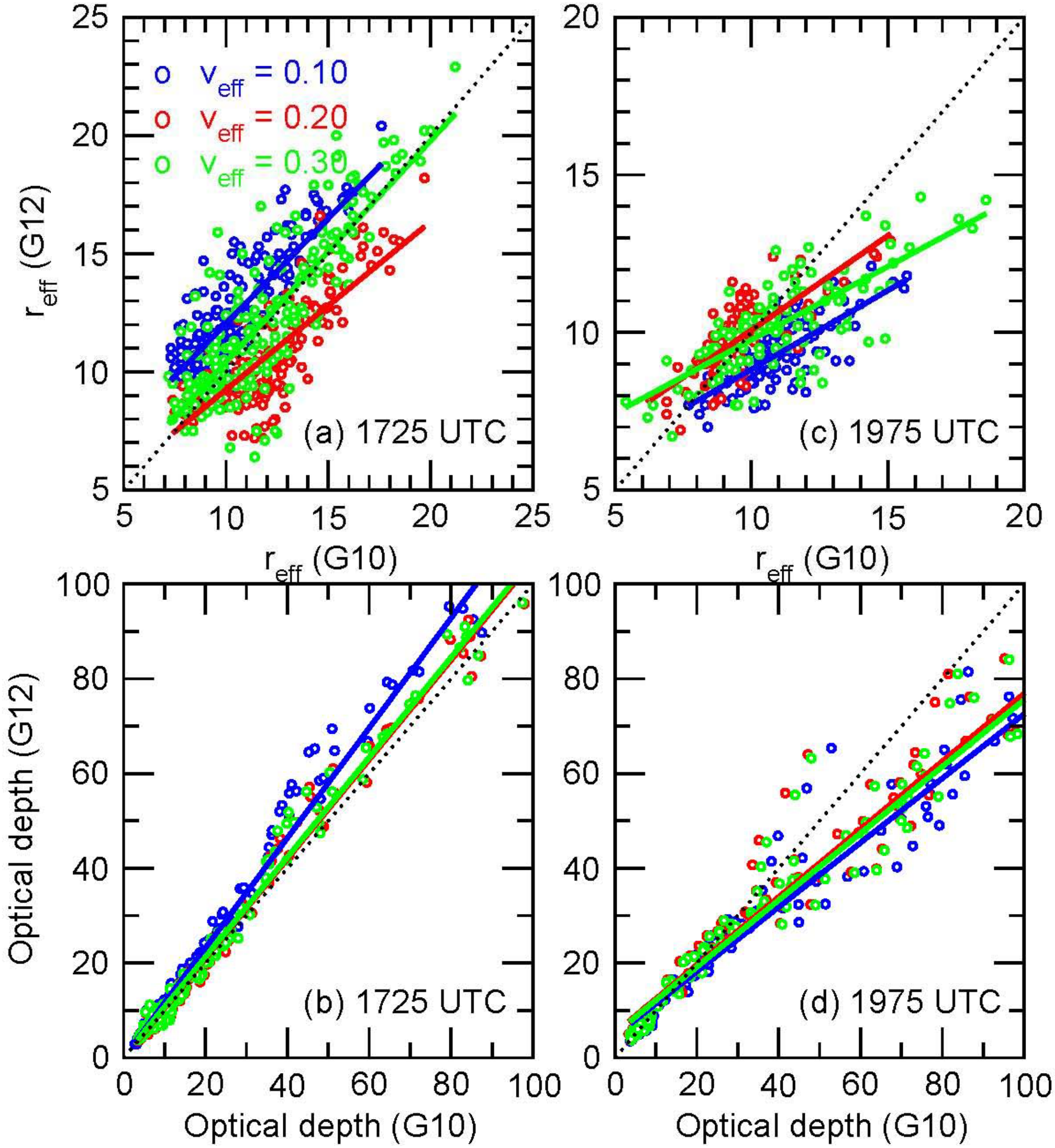

Figure 8. Correlation of retrievals of effective radius (a, c) and optical depth (b, d) from overlapped observations by GOES-10 and GOES-12 at two times on October 19. See Table 1 for correlation statistics.

Table 1. Mean differences between GOES-10 and GOES-12 optical depths ($\Delta\tau$) and effective radius (Δr_{eff}), linear correlation coefficients (R^2), and mean scattering angles for matched data in Figures 7 and 8. Times for each day given in UTC.

	$\Delta\tau$			Δr_{eff} (μm)			R^2			Θ (°)	
v_{eff}	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3	G10	G12
Apr 11											
1725	-0.1	-0.1	0.1	-0.9	0.7	0.6	0.86	0.83	0.87	118	164
1975	-0.6	-1.2	-1.1	1.1	-0.3	0.3	0.96	0.95	0.97	153	133
Oct 19											
1725	-3.0	-1.0	-1.2	-2.0	1.5	-0.3	0.84	0.83	0.83	124	168
1975	9.1	6.4	6.9	1.7	-0.3	0.8	0.75	0.76	0.76	161	131

Concluding Remarks

These preliminary results demonstrate that the effective variance, or the spectral dispersion, of the water droplet size distribution used in generating the reflectance models for remote sensing can have a significant effect on the retrieved cloud properties. The impact depends on r_{eff} and scattering angle. Use of the wrong spectral dispersion could induce hour-to-hour variations in the GOES retrievals because of the changing scattering angle and a constant effective variance is used in the retrievals.

The use of large effective variances appears to reduce scattering angle biases that can be due to 3D cloud effects, as well as the assumed droplet size distribution. These large values of variances are not unreasonable, based on observations especially in continental air masses. These early findings are consistent with the analysis of Khaiyer et al. (2005), who determined that large effective variances yield the best match with surface-based liquid water path measurements.

Only a limited number of satellite angular pairs have been analyzed so far. Future research will expand the testing of the different effective variance models for a wider range of angles and evaluate the improvements in terms of cloud temperature, optical depth, and fraction to determine if any sort of dependencies exist. Later studies will also focus on reconciling the apparent need to use large variances and will examine the optimal model value over land and water surfaces. Ideally, a variable variance would be desirable, but determining the correct value will be difficult from a single angle. Despite the shortcomings, optimizing the models for the droplet distributions should lead to better model parameterizations as well as improved satellite remote sensing.

Acknowledgements

The Environmental Sciences Division of the U.S. Department of Energy Interagency Agreement DE-AI02-97ER62341 under the ARM Program supported this research.

References

Ayers, JK, P Minnis, R Palikonda, PW Heck, and RF Arduini. 2005. "Evaluation of Cloud Properties Derived from Dual-View Satellite Data over the Continental United States." In *Proceedings of the Fifteenth Annual ARM Science Team Meeting*, Daytona Beach, Florida, March 14 – 18.

Hansen, JE. 1971. "Multiple scattering of polarized light in planetary atmospheres. Part II. Sunlight reflected by terrestrial water clouds. *Journal of Atmospheric Science* 28, 1400-1426. In *Proceedings of the Fifteenth Annual ARM Science Team Meeting*, Daytona Beach, Florida, March 14 – 18, 2005.

Khaiyer, MM, RF Arduini, P Minnis, J Huang, R Palikonda, G Nowicki, and B Lin. 2005. "Comparison of cloud liquid water paths over ARM SGP using satellite and surface data: validation of new models." In *Proceedings of the Fifteenth ARM Science Team Meeting*, Daytona Beach, Florida, March 14 – 18, 2005.

Martin, GM, DW Johnson, and A Spice. 1994. "The measurement and parameterization of effective radius of droplets in warm stratocumulus clouds." *Journal of Atmospheric Science*, 51:1823-1842.

Miles, NL, J Verlinde, and EE Clothiaux. 2000. "Cloud droplet distributions in low-level stratiform clouds." *Journal of Atmospheric Sciences* 57:295-311.

Minnis, P, DP Garber, DF Young, RF Arduini, and Y Takano. 1998. "Parameterization of reflectance and effective emittance for satellite remote sensing of cloud properties." *Journal of Atmospheric Science*, 55:3313-3339.

Minnis, P, L Nguyen, WL. Smith, Jr, MM Khaiyer, R Palikonda, DA Spangenberg, DR Doelling, D Phan, GD Nowicki, PW Heck, and C Wolff. 2004. "Real-time cloud, radiation, and aircraft icing parameters from GOES over the USA." In *Proceedings of the Thirteenth AMS Conference Satellite Oceanography and Meteorology*, Norfolk, Virginia, September 20-24, CD-ROM, P7.1.

Nakajima, T and MD King. 1990. "Determination of optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: Theory." *Journal of Atmospheric Science* 47:1878-1893.

Politovich, MK. 1993. "A study of the broadening of droplet size distributions in cumuli." *Journal of Atmospheric Science* 50:2230-2244.

Rossow, WB and RA Schiffer. 1999: "Advances in understanding clouds from ISCCP." *Bulletin of the American Meteorological Society*, 80(10), 2261-2287.