Comparison of Cloud Liquid Water Paths Over Atmospheric Radiation Measurement Southern Great Plains Using Satellite and Surface Data: Validation of New Models

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Introduction

Cloud liquid water path (LWP) is a crucial parameter for climate studies, especially for use in general circulation models. To provide a long-term, large-scale dataset of this important parameter, the Visible Infrared Solar Split-Window Technique (VISST) retrieval method is used to derive LWP over the Atmospheric Radiation Measurement (ARM) Climate Research Facility Southern Great Plains (SGP) site. For accurate derivation of LWP, a priori knowledge or assumption of several parameters is required. For the VISST technique, values of the optical depth and effective radius are required to determine LWP. VISST determines optical depth by matching satellite-observed 0.65-µm reflectances to a parameterization of theoretically derived reflectance calculations for seven water droplet size distributions (Minnis et al. 1998). It derives droplet size effective radius in similar manner by matching the observed 3.9-µm reflectance to the parameterized model reflectances. These models are dependent upon an assumed particle size distribution, which is governed by the variance in the water droplet size distribution.

For the current operational VISST retrievals, modified gamma distributions of water droplet sizes were defined based on various effective radii using a constant effective variance of 0.10. Since these assumptions are used to determine the reflectance tables that allow VISST to derive optical depth and effective radius, they will ultimately affect LWP retrieval. To evaluate the effect of particle size distributions on the derivation of LWP in VISST, it is necessary to retrieve cloud properties using the same technique with variable values of effective variance v_{eff}. The results can be evaluated using an independent measurement such as surface-based microwave radiometer (MWR) retrievals of LWP. In this paper, VISST retrievals are performed using Geostationary Operational Environmental Satellite (GOES) data over the ARM SGP site. The results are compared to values of LWP derived from MWR data taken at the ARM SGP Central Facility (CF).

The evaluation of the accuracy of LWP derived using these models, when compared to the ARM MWR LWP data, will be helpful in determining appropriate values of effective variance to employ in VISST reflectance models. This, in turn, should improve accuracy in the VISST-derived parameters of optical depth, effective radii, and LWP. VISST can then provide more accurate microphysical information, and over a much larger scale domain than in situ data can.

Methodology

The VISST uses 0.65, 3.9, 11, and 12-µm data to retrieve cloud and radiative properties (Minnis et al. 1995) at the GOES nominal resolution of 4 km. VISST was applied to 2002 GOES-8 (G8) data over the SGP site (32°N – 42°N, 91°W – 105°W). GOES-10 (G10) and GOES-12 (G12) data from other selected days are used to expand the analyses. Cases were from selected days having persistent low-level warm cloud (daytime cases, with approximately 2 or more hours of 100% water cloud, and an effective cloud temperature Tc > 273.15 K). Seven new 0.65 and 3.9 µm cloud reflectance models, incorporating different size distribution variances, were used in the VISST processing of the selected images. A control run was performed using the current cloud reflectance model with $v_{eff} = 0.10$. The theoretical background of the derivation of these models is given by Arduini et al. (2005).

These eight sets of cases are analyzed to determine the sensitivity of the derived LWP to the assumed size distribution variance. The cloud reflectance models include bidirectional reflectances and albedos for 21 solar and viewing zenith angles, 24 relative azimuth angles, 13 optical depths ranging from 0.25 to 128, and 9 water droplet radii between 2 and 32 µm. Variances for the seven models are 0.01, 0.02, 0.05, 0.10, 0.15, 0.20, and 0.30. The eight sets of VISST-derived LWPs were averaged over a 20-km radius around the CF and compared to 30-minute averages of ARM MWR-derived LWP (Liljegren et al. 2001). Averages of SGP LWP were used if there were at least 85 valid MWR observations within a 30-minute window. Validity was determined on the basis of sky infrared temperature (if available, Tsky > 100 K), absence of a wet window, LWP > -40 gm^{-2}, and the quality flag indicating the data were acceptable.

Results

To illustrate the sensitivity of VISST-retrieved LWP to the use of reflectance models having different variances, several persistent water cloud cases (probably best classified as stratiform type clouds) were selected from G8 data during the year 2002. The days chosen include 2, 23, and 26 April; 3, 11, and 24 May; and 5 June 2002. Figure 1 shows the large-scale cloud fields and two of the retrieved cloud parameters at 1615 Universal Time Coordinates (UTC), 2 April 2002. Large areas of the scene are covered by both warm and supercooled liquid clouds, with large patches of overlying thin cirrus clouds

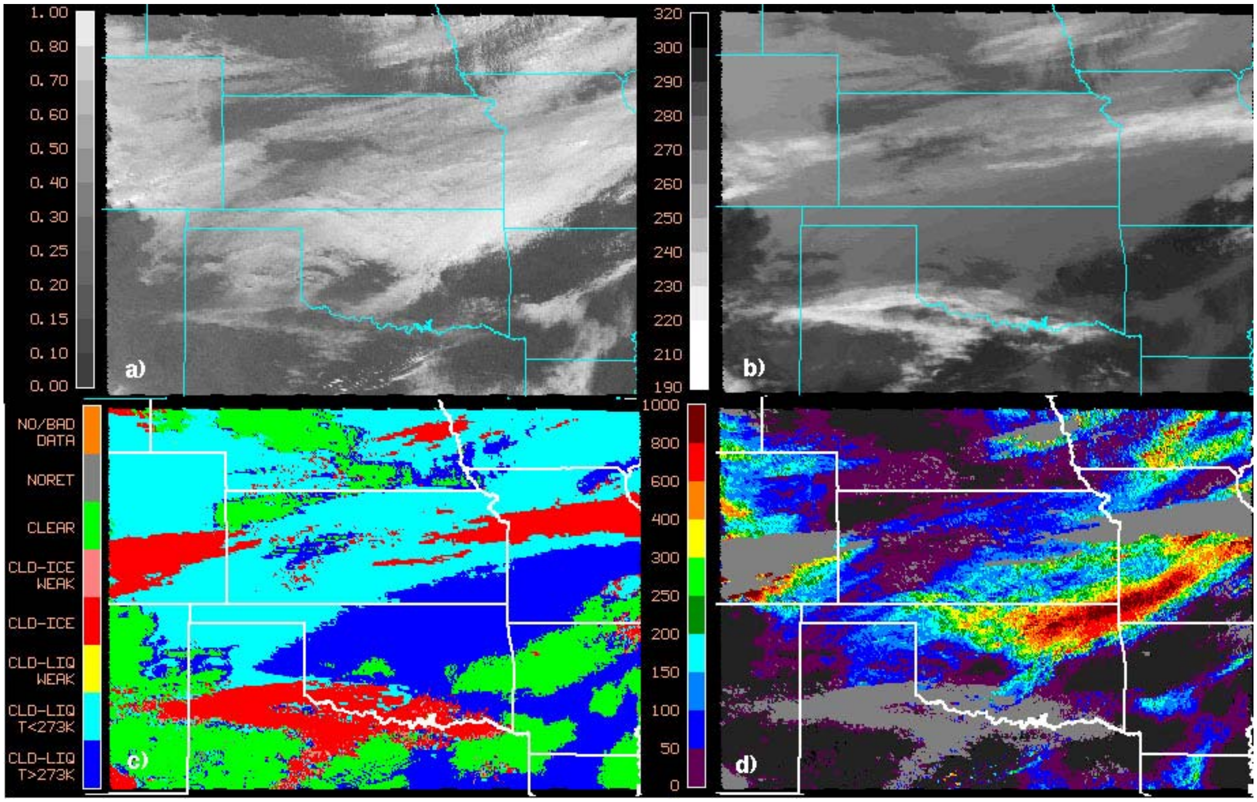

Figure 1. GOES-8 imagery and VISST retrievals over the ARM SGP domain, 1615 UTC, 2 April 2002. a) 0.65-µm reflectance, b) 10.7-µm brightness temperature (K), c) cloud phase, and d) LWP in gm^{-2}.

(Figure 1c). Some of the thinnest cirrus clouds evident in Figure 1b are misclassified as supercooled clouds because they overlie the stratus clouds and are too thin to significantly affect the derived cloud properties. The LWP values (Figure 1d) are mostly less than 200 gm^{-2}, except over northern Oklahoma, southern Missouri and Iowa. The brightest scenes (Figure 1a) correspond to the largest values of LWP.

Figure 2 compares the 62 matched retrievals of LWP from G8 using VISST and the eight different reflectance models with LWP from the CF MWR. The control cases, shown in Figure 2a, were processed with the original reflectance model (0.10 effective variance in size distribution), and yield a bias of 14.3 gm^{-2} and a standard deviation (SD) of 83.1 gm^{-2}. The LWP comparisons are presented in order of increasing v_{eff} for the VISST reflectance models. The bias increases from 7.2% for v_{eff} =0.01 to 9.2% for v_{eff} = 0.10. It then drops with increasing v_{eff} down to 2% for v_{eff} = 0.2, then increases up to 6.1% for v_{eff} = 0.3. The CTRL case differs from MOD10 because the 3.9-µm reflectance model used here is a simplified version of the CTRL case, which breaks the 3.9-µm bandpass into six different intervals. Although the smallest SD coincides with the smallest bias (Figure 2g), the SD varies by only 3 gm^{-2}. This lack of variability may be explained by the SD being dominated by a few outlying points (green). A close inspection of the results indicates that the points with large scattering angles show much less dispersion in Figure 2g than in any of the cases while there is little variation in their locations for v_{eff} < 0.10.

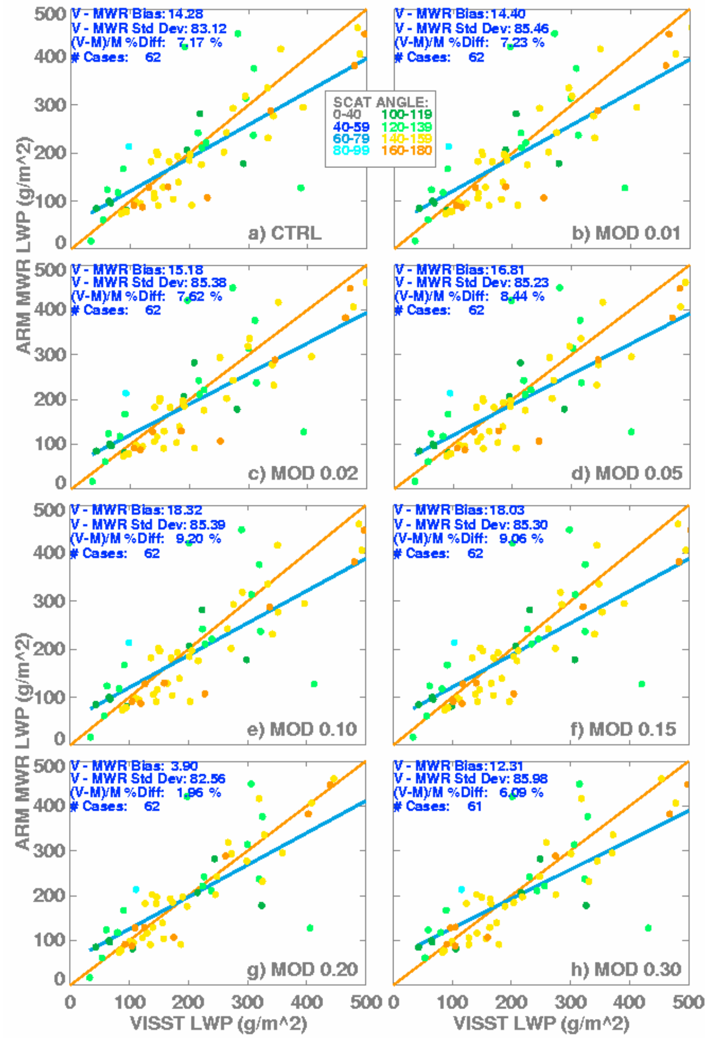

Figure 2. VISST-retrieved LWP using the different reflectance models compared to the LWP from the CF MWR. ARM MWR, color coded by scattering angle (see legend). a) control case, processed with original reflectance model (employing a 0.10 variance in size distribution; b-h) variable values of v_{eff} indicated by the number after MOD, which is 100 times v_{eff}. The one-to-one fits shown in yellow, line fits in turquoise.

Discussion

The biases for the 0.01 – 0.15 variance models range from 14.3 – 18.3 gm^{-2}, and the SDs around 85 gm^2. Compared to the control case, they do not show any real improvement. However, the 0.20 and 0.30 variance models both show improvement in the biases of observed and retrieved LWP compared to the control case, with biases of 3.9 and 12.3 gm^{-2} respectively. The larger effective variance models may show better agreement with respect to the ARM MWR LWP because they allow for a greater chance of correctly diagnosing at least some of the droplet sizes within the observed cloud. However, not all observed clouds may have the sort of distribution of droplet sizes found in the clouds in these selected cases. The mechanisms responsible for production of different cloud types can produce vastly different droplet size distributions. Politovich (1993) found that portions of cumulus clouds with turbulent mixing had wider spectral dispersions (proportional to effective variance) than portions of the cloud affected solely by an updraft. However, Miles et al. (2000) found that for both marine and continental stratus clouds, droplet size distribution width increased with height. Since the clouds chosen for this study were persistent low-level warm water clouds more in line with the cases of Miles et al. (2000), the 0.20 variance model may work well for these type of clouds, but perhaps not for others like newly formed cumulus.

Since the 0.20 and 0.30 variance models both show improvement in the biases compared to the control case, the use of these models is investigated further. Improvement in the accuracy of LWP retrievals, at least for these cases, seems to be one effect of using these models; however impacts on optical depth and effective radius are important considerations that must be evaluated. Figure 3 shows the impact of using larger effective variances on the retrievals of cloud optical depth (Tau) and effective radius (R_e), as well as LWP. For the 83 available points (additional data to that used in Figure 2 was added, including days 16 and 25 October 2002), the changes in Tau relative to the control (CTRL) cases are only 3.0% and 3.7% for v_{eff} = 0.2 and 0.3, respectively, with small SDs. The corresponding changes in R_e are slightly greater than those for Tau, but one is negative and the other is positive. The scatter is relatively more pronounced for effective radius than it was for Tau, indicating that the increased variance has a greater effect on this parameter. The differences in the sign of the changes in R_e but not in Tau indicate why the LWP improve for v_{eff} f = 0.2 but less so for v_{eff} = 0.3. Both Tau and R_e decrease in the former case causing LWP to drop, while the rise in Re for the latter case tends to offset the decrease in Tau.

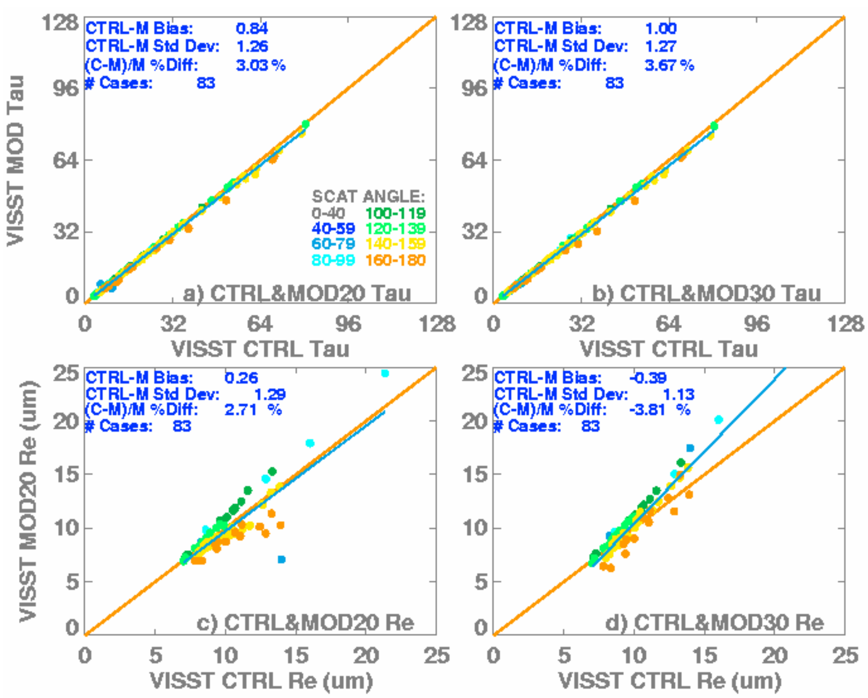

Figure 3. Comparison of Tau for Control (CTRL) and a) v_{eff} = 0.20, and b) v_{eff} = 0.30 (MOD30). Comparison of R_e for CTRL and a) v_{eff} = 0.20, and b) v_{eff} = 0.30 (MOD30). The one-to-one fits shown in yellow, line fits in turquoise.

The increased scatter in R_e, brought by the higher effective variances, calls for some additional investigation into the effects of these models. The color-coding by scattering angle of the points in Figures 3c, d indicates some notable striations in this parameter. These results along with those discussed for Figure 2g confirm the dependence of the retrieval changes with v_{eff} on the scattering angle seen in the theoretical calculations of Arduini et al. (2005). The reflectance models tested here rely on simplified parameterizations of radiative transfer and do not reproduce the original calculations perfectly. In addition, 3D cloud features may create more complicated scattering effects than can be reproduced accurately by the reflectance models, which assume plane-parallel clouds.

One way to begin gauging the scattering angle impacts on the LWP retrievals is to compare matched retrievals using G10 and G12 data, which observe large portions of central North America at different scattering angles. For a given location, the G10 and G12 scattering angles reverse from morning to afternoon as the relative azimuth angle switches. Figure 4 shows the 0.20 variance model employed in seven daytime G10 and G12 VISST retrievals from 18 October 2004 over the CF. The results are compared to the ARM MWR LWP for scenes with more than 90% water cloud coverage with Tc > 270.15 K. In Figure 4a, the control LWP (G10) shows a great deal of scatter (86.1 gm^{-2}) and a large bias of 98.5 gm^{-2} compared to LWP (MWR). The control LWP (G12) shows a large bias compared to LWP (MWR) as well in Figure 4b. The use of v_{eff} = 0.20 reduces the LWP (G10) bias by a factor of three in Figure 4c, but it slightly increases the bias for LWP(G12) as seen in Figure 4d.

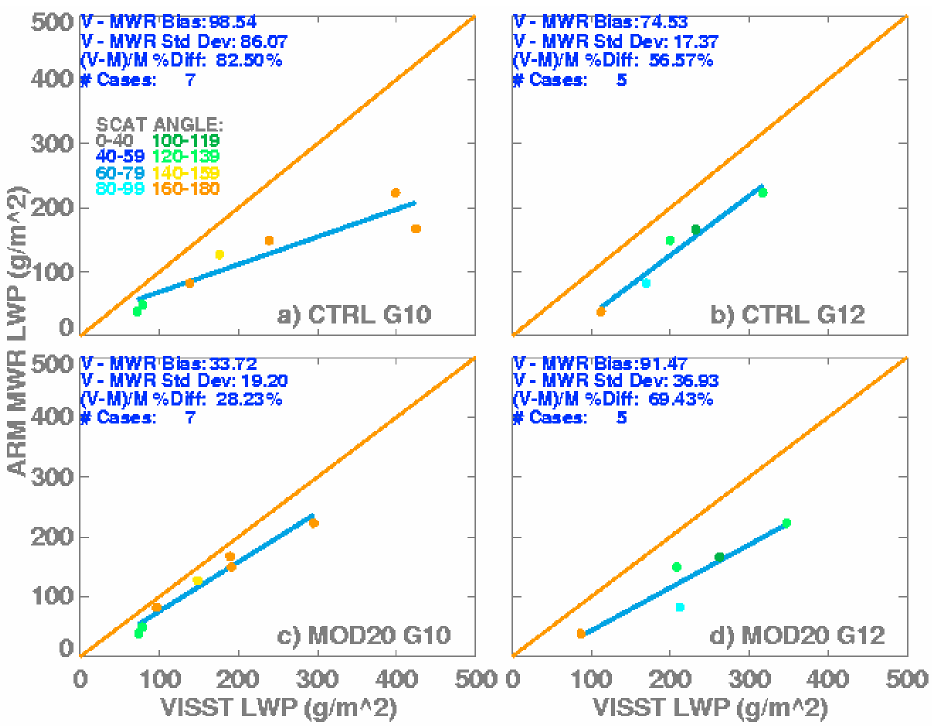

Figure 4. Daytime 18 October 2004 G10 and G12 VISST LWP retrievals for >90% water cloud control and v_{eff} = 0.20 cases, color coded by scattering angle (see legend). Comparisons are between ARM MWR LWP and a) Control GOES10 (CTRL); b) Control GOES12 (CTRL); c) the 0.20 variance model

(MOD20) for GOES10; and d) GOES12 with the 0.20 variance model (MOD20). The one-to-one line is shown in yellow, and the line fits are in turquoise.
The cases with large scattering angles (160° -180°) show considerable improvement, clustering closer to the one-to-one correlation line. The lone 140° -159° case improved as well, while the 120° -139° cases changed only a little. It is important to note that the magnitude of LWP for the 120° -139° cases may have been too small to show much sensitivity to scattering angle. Oddly, while LWP (G10) improved overall, some LWP (G12) cases seemed to worsen slightly. The number of cases presented here is too small to determine exhaustively the effect of scattering angle in these various reflectance models, so further work is needed to determine this.

To illustrate some of the large-scale impacts of this model, Figure 5 shows the G10 retrieved LWP at 1645 UTC, 18 October 2004 using v_{eff} = 0.2 and 0.1. The changes are subtle, but noticeable as a general reduction in LWP when the larger value of veff is used. Contours of the greatest values encompass slightly less area than when v_{eff} = 0.1. The changes in LWP will vary from hour to hour depending on the particular scattering angle. At some scattering angles, no changes occur when altering v_{eff}. More work is needed to determine the impacts of the effective variance in reflectance models.

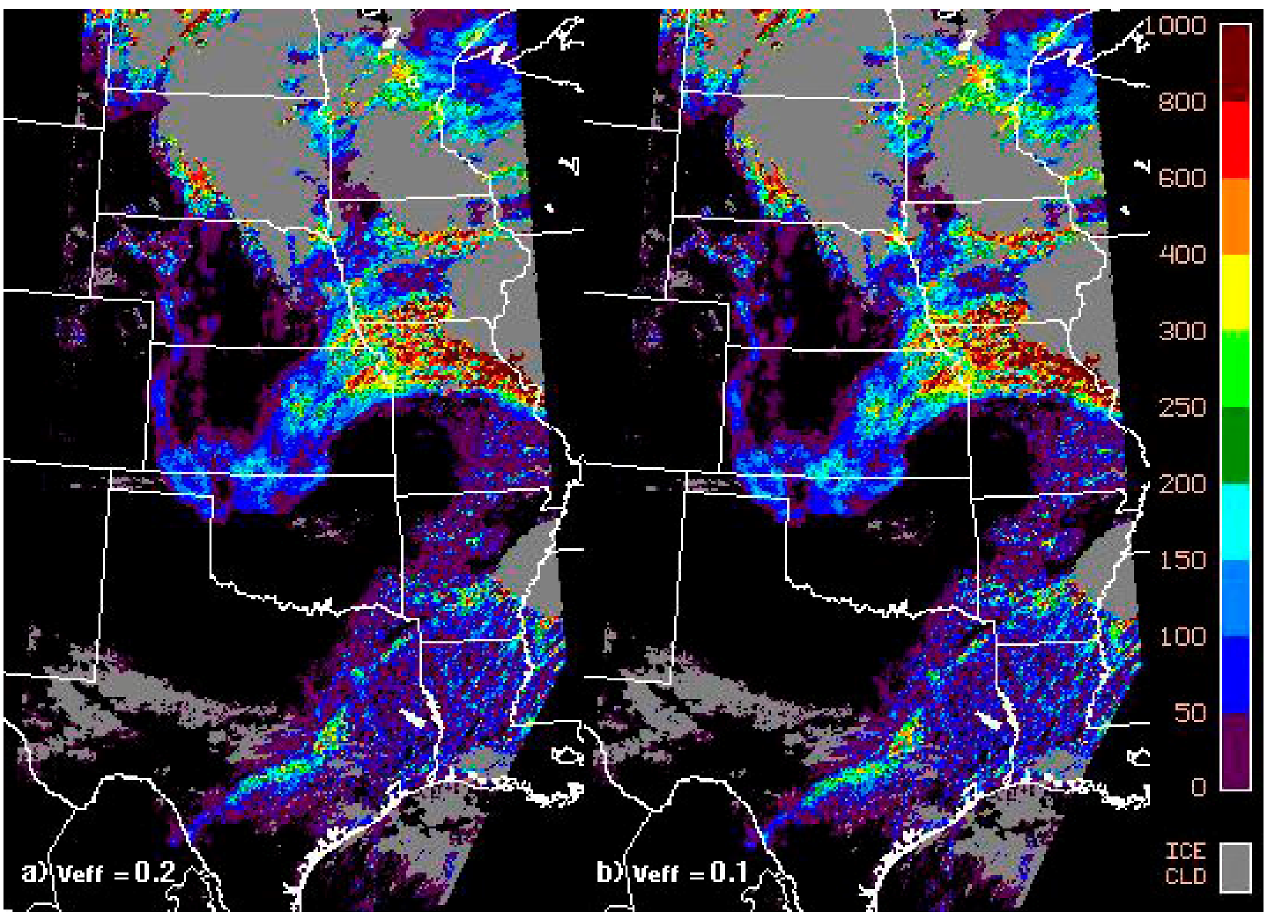

Figure 5. 1645 UTC 18 October 2004 GOES-10 retrieved LWP, using a), v_{eff} = 0.20 and b) control.

Summary and Future Work

Discussion

Satellite retrievals of parameters such as LWP are useful for quantifying the cloud microphysical characteristics over a large region. However, retrieval of such parameters is heavily dependent upon many assumptions, including particle size distributions within reflectance models employed to derive optical depth, effective radius, and ultimately LWP. Varying size distributions in these reflectance models were tested on various G8 cases to determine the optimal effective variance for accurately retrieving LWP. It was found that the use of larger effective variances had a dramatic effect in many cases. Specifically, the 0.20 and 0.30 variances in the size distribution seemed to improve most cases of LWP when compared to independent LWP measurements using the ARM MWR at the CF. However, the chosen cases were mostly stratiform clouds, so additional work is needed to determine if the improvements seen in this study translate to other cloud types.

The reflectance models employing these differing effective variances may also have differing impacts based on scattering angle. A particular value of effective variance in the reflectance models may yield good results for derived parameters at one scattering angle, but bad ones at another. Some work towards this problem has been initiated by Ayers et al. (2005) and Arduini et al. (2005). The results presented here are preliminary, but encouraging. More tests are needed to determine the optimal effective variance for satellite retrievals of LWP in many more conditions, including a wide range of scattering angles and cloud types. The improvements in some cases due to the larger effective variances point to some possible sources of improvement in the satellite retrieval of effective radius, optical depth, and LWP and, therefore, better data for validating and improving cloud process and climate models.

Acknowledgements

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References

Arduini, RF, P Minnis, WL Smith, Jr., JK Ayers, MM Khaiyer, and PW Heck. 2005. "Sensitivity of Satellite-Retrieved Cloud Properties to the Effective Variance of Cloud Droplet Size Distribution." In *Proceedings of the Fifteenth Annual ARM Science Team Meeting*, Daytona Beach, Florida, March 14 – 18, 2005

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.

Liljegren, J, E Clothiaux, G Mace, S Kato, and X Dong. 2001. "A new retrieval for cloud liquid water path using a ground-based microwave radiometer and measurements of cloud temperature." *Journal of Geophysical Research* (106)14,485-14,500.

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

Minnis, P, DP Garber, D F 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, DP Kratz, JA Coakley, Jr., MD King, D Garber, P Heck, S Mayor, DF Young, and R Arduini. 1995. Cloud Optical Property Retrieval (Subsystem 4.3). "Clouds and the Earth's Radiant Energy System (CERES) Algorithm Theoretical Basis Document, Volume III: Cloud Analyses and Radiance Inversions (Subsystem 4)," NASA RP 1376 Vol. 3, edited by CERES Science Team, pp. 135-176.

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