Retrieval of Ice Cloud Properties Using Variable Phase Functions

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Abstract. An enhancement to NASA Langley's Visible Infrared Solar-infrared Split-window Technique (VISST) is developed to identify and account for situations when errors are induced by using smooth ice crystals. The retrieval scheme incorporates new ice cloud phase functions that utilize hexagonal crystals with roughened surfaces. In some situations, cloud optical depths are reduced, hence, cloud height is increased. Cloud effective particle size also changes with the roughened ice crystal models which results in varied effects on the calculation of ice water path. Once validated and expanded, the new approach will be integrated in the CERES MODIS algorithm and real-time retrievals at Langley.

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INTRODUCTION

Cloud macrophysical and microphysical cloud properties are retrieved at NASA Langley Research Center in near-real time over a variety of domains from multi-spectral imagery obtained from various satellite instruments, including Geostationary Operational Environmental Satellite (GOES), Spinning Enhanced Visible InfraRed Imager (SEVIRI) and Moderate Resolution Imaging Spectroradiometer (MODIS). For daytime imagery, the Visible Infrared Solar-infrared Split-window Technique (VISST), as described in Minnis et al. (1995)[1], is applied to 0.65, 3.9, 10.8 and 13.3 µm imagery to derive cloud amount, temperature, height and optical depth, as well as cloud microphysical characteristics such as particle size, phase and liquid or ice water path. To date, VISST has employed a set of cloud reflectance and emissivity models, as well as adding-doubling code, (Minnis et al. 1995, 1998)[1,2] using water spheres and smooth hexagonal ice crystals to construct the top-of-atmosphere radiances that are compared to observed radiances. For ice clouds, the assumption to use a set of size distributions for randomly oriented, smooth crystals has validated well for a multitude of cloud types and locations (e.g., Mace et al. 2005[3]; Nguyen et al. 2008[4]), but multi-layer scenes and thin cirrus clouds are more problematic in some situations. On average, VISST-derived ice water paths for thin cirrus clouds compare well with ground-based measurements while cloud temperature and optical depth can be overestimated (Mace et al. 2005)[3].

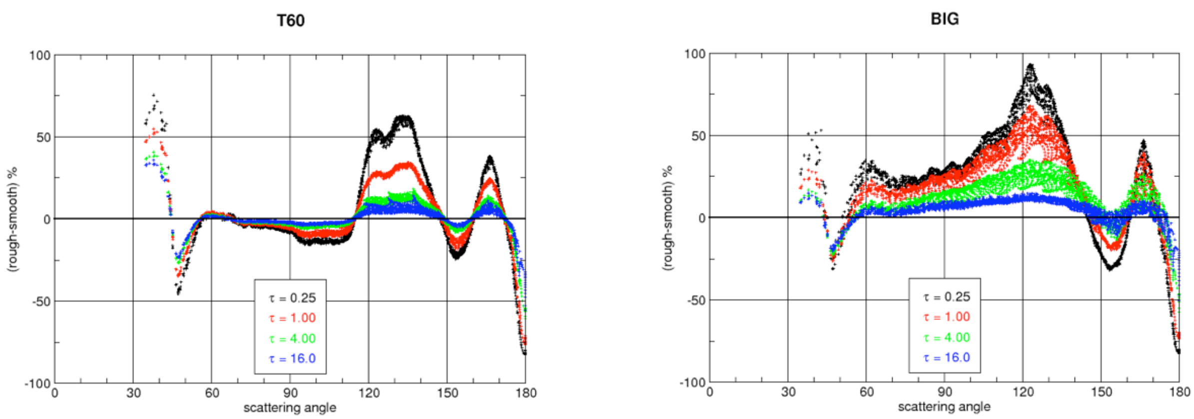
A separate recent enhancement to VISST, a multi-layer detection scheme that utilizes CO2-absorbing channels, is currently addressing deficiencies in multi-layer situations and simultaneously acting as an indicator when VISST retrievals may not be capable of accurately characterizing a particular thin cirrus cloud (Chang et al. 2008)[5]. An enhanced retrieval scheme, VISST-R, is being developed to account for these errors by incorporating a new multi-layer algorithm and new ice cloud phase functions, based on Yang et al. (2008)[6,7], that utilize hexagonal crystals with roughened surfaces. The accompanying changes in asymmetry factors modify the modeled visible and solar-infrared cloud reflectances, hence the retrieved microphysics. This paper presents the rationale and implementation scheme for the new algorithm, as well as first results from a case study using GOES-12 data.

METHODOLOGY

To judge the feasibility and potential impact of the roughened ice crystal phase functions, new cloud reflectance lookup tables were created for 0.65 and 3.9 µm channels of GOES that mimic the existing VISST models but with the impact of the roughened crystals accounted for. For this study, smooth ice crystals have a roughness factor, σ, of 0.0 while rough ice crystals have σ = 0.5. As expected, these new models exhibit large differences in cloud reflectance when compared to the smooth ice crystal models as a function of scattering angle(Yang et al. 2008)[7], hence it should be possible to find satellite imagery with appropriate scattering angles and clouds and in order to test the impact of the rough models.

Examination of Model Data

In order to choose an appropriate case study for applying the roughened models, it is necessary to examine situations where the changes are expected to be substantial. Figure 1a shows that for a particular ice cloud particle size distributions (T60) made up of hexagonal columns with an effective diameter, D_{eff}, of 30.4 µm, that large differences between the smooth and rough models at 0.65 µm exist at backscatter and from about 120 to 160 degrees in the vicinity of the rainbow feature. These large differences have their largest absolute values for thin clouds, i.e., when cloud optical depth, τ, is low, indicating that for this model the impact of the roughened ice crystal models will maximize for thin ice clouds at backscatter and the rainbow feature.



a) b)

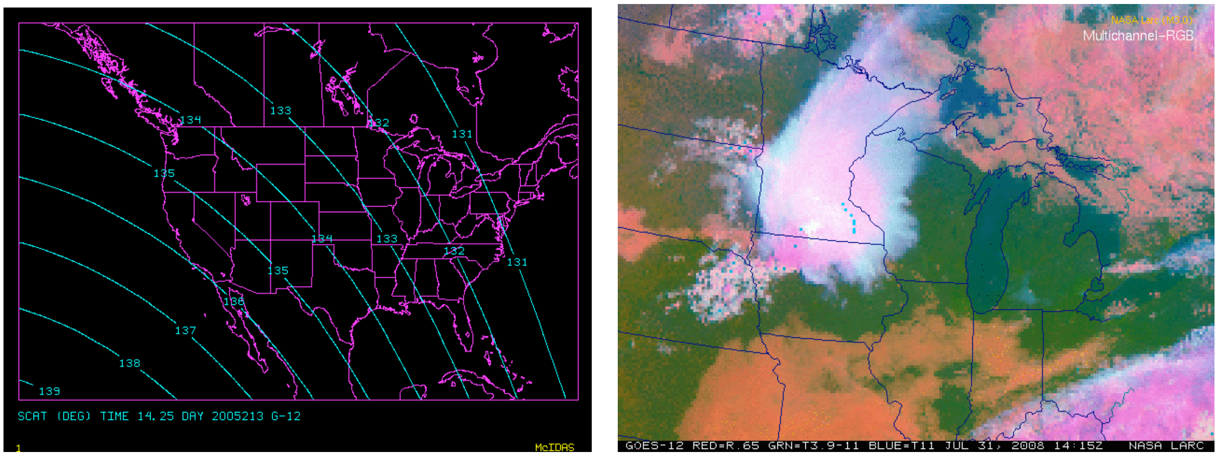
FIGURE 1. Modeled 0.65 µm ice cloud reflectance difference (rough – smooth) as a function of scattering angle for cloud optical depths ranging from 0.25 to 16.0 for a) a size distribution (T60) with D_{eff} = 30.4 µm and for b) a size distribution (BIG) with D_{eff} = 134.9 µm.

In Figure 1b, the same differences are shown between the rough and smooth models, but for a much larger size distribution (BIG) with D_{eff}, = 134.9 µm. While the behavior of the differences as a function of scattering angle has a similar shape as those of the smaller ice crystals in Fig. 1a, the differences are much larger for a thin clouds at almost all scattering angles less than about 135º. While the NCON and T60 models are just two of the nine ice crystal size distributions that are used in VISST, other models exhibit similar behavior.

Case Study Selection

In order to select a test case for GOES-12 imagery, it is necessary to choose a location, time of year and time of day with a scattering angle near the maximum differences of Fig. 1. The scattering angles for GOES-12 from July 31, 2008, at 14:15 UTC are shown in Figure 2a with the accompanying false color image from the North Central United States from the GOES-12 imager is shown in Figure 2b.

The large mesoscale convective system (MCS) over Minnesota and Wisconsin has a large anvil shield spreading generally to the east and cirrus surrounding the large convective core in almost all directions. This case is chosen for the case study because the scattering angle from Fig. 2a is approximately 132º, near the area of largest expected differences between rough and smooth ice crystal models and because of the large range of optical depths that is expected from the edge of the MCS to its center.

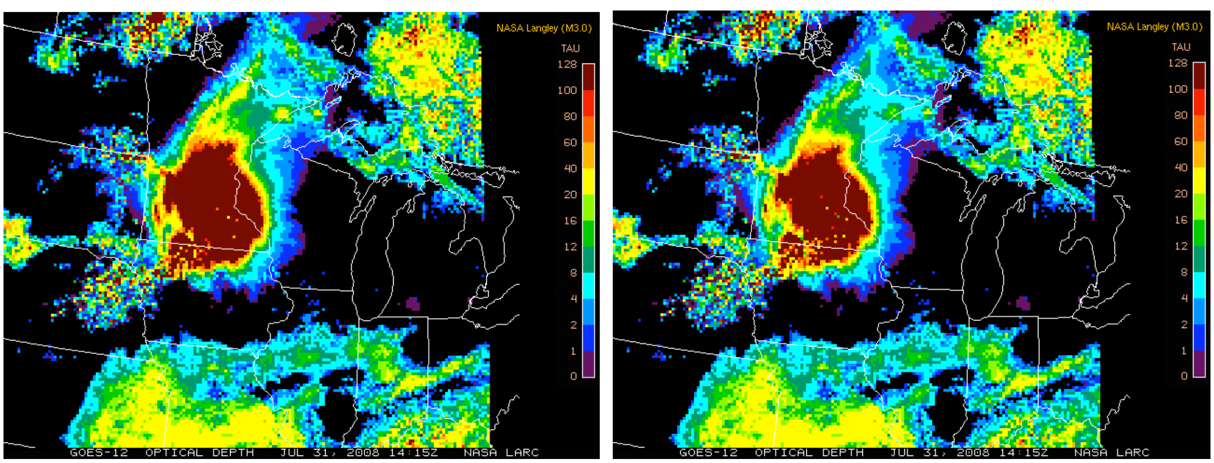


a) b)

FIGURE 2. a) Scattering angle for GOES-12, July 31, 2008 at 14:15 UTC over continental US and b) false color image of actual GOES-12 imagery for same day and time over North Central US.

RESULTS

Assessment of the impact of the rough ice crystal models is first done by conducting a VISST retrieval using no surface roughness and then conducting the same retrieval using only roughened ice crystals. For the GOES-12 imagery of Fig. 2b, optical depth retrievals are shown in Figure 3.

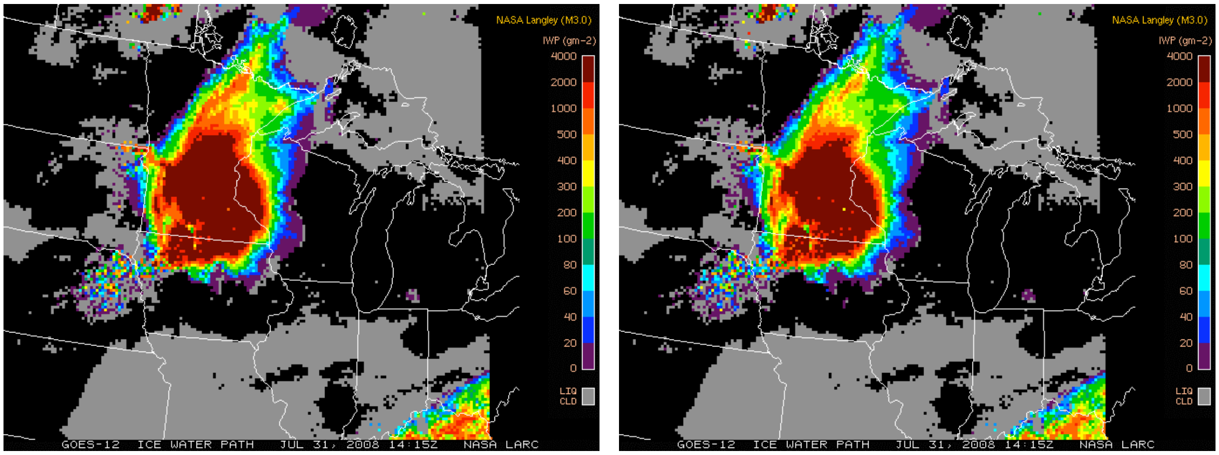


a) b)

FIGURE 3. For domain of Fig. 2b, VISST optical depth retrieval for 31 July 2008 at 14:15 UTC using a) $\sigma = 0.0$ (smooth) and b) $\sigma = 0.5$ (rough). Both ice and water cloud optical depths are shown.

While the differences between Figs. 3a and 3b are small, it is obvious that near the eastern and northeastern areas of thin cirrus (over western and northwestern Wisconsin, as well as northeastern Minnesota optical depth has decreased. This is as expected given that Figs. 1a and 1b indicated that thin clouds would show the biggest differences between smooth and rough models. The decrease of the thin cloud optical depths causes a slight increase in effective cloud heights of about 0.3km (not shown) in the thinnest portion of the clouds so that they are closer in height to the adjacent thicker clouds. The effective ice particle size differences are variable, with thicker portions of the cloud showing small increases in D_{eff} while some thinner areas show a slight increase.

Figure 4 shows the accompanying retrieval of ice water path and indicates that the variable changes in D_{eff} and the decreases in τ have compensated to some degree. Some of the areas of Fig. 3 that saw decreased τ have also seen a decrease in IWP, but most remain unchanged.



a) b)

FIGURE 4. For domain of Fig. 2b, VISST ice water path retrieval (g/m^2) for 31 July 2008 at 14:15 UTC using a) $\sigma = 0.0$ (smooth) and b) $\sigma = 0.5$ (rough).

The direction of the differences in cloud optical depth, height, effective particle size and ice water path are as expected if the thin clouds are indeed made up of non-smooth ice crystals, although the validity of any of the retrieved parameters remains to be seen.

CONCLUSIONS

This small case study shows only that a more rigorous set of test cases and a more sophisticated algorithm has the potential to utilize the rough ice crystal models of Yang et al. (2008)[6,7] in order to address some of the biases that have been shown in VISST results. The VISST results behave as expected when the roughened models are used, so the next step will be to invoke those models only when necessary since the vast majority of ice clouds using the smooth models have validated well. VISST-R, a scheme that will use results from the CO2-based approach of Chang et al. (2008)[5] is being developed and will be tested on CERES MODIS imagery and GOES imagery.

REFERENCES

1. P. Minnis, P., D. P.,Kratz, J. A.,Coakley, Jr., M. D. King, D. P. Garber, P. W. Heck, S. Mayor, W. L. Smith, Jr., D. F. Young, R. A. Arduini, 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 Determination of Improved Top of Atmosphere Fluxes (Subsystem 4)", *NASA RP-1376*, **Volume III**, edited by CERES Science Team, pp. 135-176 (December 1995).
2. P. Minnis, D. P. Garber, D. F. Young, R. F. Arduini and Y. Takano, Parameterization of Reflectance and Effective Emittance for Satellite Remote Sensing of Cloud Properties. *J. Atmos. Sci*., **55**, 3313-3339 (1998).
3. G. G Mace, Y. Zhang, S. Platnick, M. D. King, P. Minnis, P. Yang: Evaluation of cirrus cloud properties derived from MODIS radiances using cloud properties derived from ground-based data collected at the ARM SGP site, *J. Applied Meteorol*., **44**, 221-240 (2005).
4. L. Nguyen, P. Minnis, D. A. Spangenberg, R. Palikonda, D. N. Phan, and M. L. Nordeen, Validation of real-time GOES products using GLAS and CALIPSO data. AMS 5th GOES Users' Conf., CD-ROM, P1.63 (2008).
5. F. Chang, P. Minnis, B. Lin, R. Palikonda, M. Khaiyer, and S. Sun-Mack, Retrieving cloud properties for multilayered clouds using simulated GOES-R data. AMS 5th GOES Users' Conf., New Orleans, LA, January 23-24, CD-ROM, P1.69 (2008).
6. P. Yang, G. W. Kattawar, G. Hong, P. Minnis and Y. Hu, Uncertainties associated with the surface texture of ice particles in satellite-based retrieval of cirrus clouds, Part I. Single-scattering properties of ice crystals with surface roughness, IEEE Transactions on Geosciences and Remote Sensing, **46**, 1940-1947 (2008).
7. P. Yang, G. Hong, G. W. Kattawar, P. Minnis and Y. Hu, Uncertainties associated with the surface texture of ice particles in satellite-based retrieval of cirrus clouds, Part II. Effect of particle surface roughness on retrieved cloud optical thickness and effective particle size, IEEE Transactions on Geosciences and Remote Sensing, **46**, 1948-1957 (2008).