Comparisons of Cloud Heights Derived from Satellite and Atmospheric Radiation Measurement Surface Lidar Data

W.L. Smith, Jr., L. Nguyen, D.P. Garber, D.F. Young
Analytical Services and Materials, Inc.
Hampton, Virginia

P. Minnis
Atmospheric Sciences Division
NASA Langley Research Center
Hampton, Virginia

J. Spinhirne
NASA Goddard Space Flight Center
Greenbelt, Maryland

Introduction

Cloud heights derived from single-channel, satellite infrared data can be relatively uncertain under certain conditions such as overlapped or optically thin clouds. During the daytime, optical depths derived from 0.63 µm visible (VIS) reflectances are used to adjust the altitude of optically thin clouds. Without the adjustment, the cloud heights are significantly underestimated diminishing the reliability and utility of the data. Therefore, at night, other data are required to determine cloud optical properties. In this paper, a new technique is developed to determine the phase, optical depth, effective particle size, and altitudes of optically thin clouds at night using combinations of the 3.7-µm or solar infrared (SI), the infrared (IR) window at 11 µm, and the 12-µm "split" window (SW) channels. These retrieval methods are tested by applying them to multispectral Geostationary Operational Environmental Satellite (GOES) data and comparing the results with Atmospheric Radiation Measurement (ARM) Program surface lidar measurements taken during several seasons over central Oklahoma. Both daytime and nighttime methods are tested for a variety of cloud conditions. This analysis provides a more comprehensive evaluation of satellite-derived cloud heights than heretofore possible.

Data

This study focuses on data collected during four recent ARM Intensive Observation Periods (IOPs), which include the Cloud Remote Sensing lOPs in April 1994 and 1995, the Single Column Model IOP in July 1994, and the ARM/Unmanned Aerospace Vehicle (UAV) IOP conducted concurrently with the ARM Enhanced Shortwave Experiment (ARESE) in October and November 1995. Radiances taken from GOES-7 (VIS and IR) and GOES-8 (VIS, IR, SW, and SI) with a nominal 4-km resolution are analyzed to derive cloud radiative and microphysical properties. National Weather Service rawinsonde data, gridded at standard levels, are used to convert cloud temperature retrievals to height. Cloud boundary estimates from the Micro Pulse Lidar (MPL) deployed at the ARM Southern Great Plains (SGP) central facility (SCF) are utilized to help validate the cloud height retrievals. (For more information about the MPL, access the World Wide Web site, http://virl.gsfc.nasa.gov/mpl.html.)

Analysis Methods

To date, cloud and top of atmosphere radiation parameters have been derived from satellite data for ARM IOPs using the Layer Bispectral Threshold Method (LBTM) during the day and a simple single IR channel threshold method at night (hereafter referred to as IRONLY). Minnis et al. (1995a) describe an LBTM analysis for the April 1994 IOP. Cloud and radiation parameters are derived for 3 layers: low (cloud heights $z_c < 2$ km), mid ($2 < z_c < 6$ km), and high ($z_c > 6$ km). Optical depths τ are derived from visible reflectance measurements by employing the parameterization described by Minnis et al. (1993). For this study, we assume a 10-µm water droplet model for low- and mid-level cloud and a cirrostratus model for high-cloud τ estimates. Cloud temperature, T_{cld}, is derived from the measured IR brightness temperature. For thin clouds during the day, T_{cld} is derived by using the VIS optical depth estimate to correct the brightness temperature measurement. Since optical depth cannot be estimated with the IRONLY method, nighttime cloud height retrievals currently provided for the ARM program are probably underestimated on average. The GOES data are analyzed for a 0.3° or 0.5° region centered on the SCF as in Minnis et al. (1995a).

To improve the retrieval of thin cloud heights at night, as well as to derive nighttime cloud optical depth and microphysical properties, a 3-channel technique is employed. It utilizes the SI, IR, and SW channels of the GOES-8 imager. This technique determines T_{cld}, cloud phase, τ, and effective cloud particle size with a minimum-error, iterative regression method that matches the observations to parameterized model emittance calculations (Minnis et al. 1995b). A 75-term polynomial defines the emittance parameterization which is a function of τ, effective ice-crystal diameter *D*, or water-droplet radius r, and the temperature difference between the cloud and surface. Brightness temperature differences (BTDs) are calculated from the satellite radiances such that

$$BTD_{24} = T_{SI} - T_{IR} \text{ and } BTD_{45} = T_{IR} - T_{SW} \qquad (1)$$

These same quantities are also computed with the emittance parameterizations assuming that all cloudy pixels are overcast and have a temperature given by an initial estimate of T_{cld} over a background with a known clear-sky temperature for each channel. The phase and a nominal particle size are also assumed for the initial computation. The calculations of BTD_{24} and BTD_{45} are repeated for both liquid and ice clouds by varying *D* or r, τ, and T_{cld} until the difference between the calculated and observed BTDs is minimized. Specifically, we minimize

$$\sum \left[\left(BTD_{24}^{obs} - BTD_{24}^{calc}\right)^2 + \left(BTD_{45}^{obs} - BTD_{45}^{calc}\right)^2 \right]. \quad (2)$$

The selected phase is based on which of the two minimum errors is smaller. Cloud height is then calculated from T_{cld} using radiosonde temperature profiles. Assuming T_{cld} to be constant permits the retrieval of *D* or r and τ at the pixel scale by iteratively adjusting τ and *D* in the parameterization until the calculated BTDs best match the observed BTDs for each pixel. For this study, each cloudy pixel is assumed to be from a single cloud layer. Multi-level cloud scenes may contaminate the retrieval of T_{cld}, r and τ with the current technique.

Results

During the IOP in April 1995, the MPL observed a persistent cirrus cloud shield for nearly three days over the SCF. Figure 1a illustrates the results of a 3-channel nighttime retrieval at 0245 UTC on April 15. The lidar data indicate that the cloud is between 11.0 and 8.4 km. The two sets of curves represent the ice crystal and water droplet solutions that best fit the observed BTDs. Ice phase is selected for the cloud because the ice solution fits the data better than the water-droplet solution. The T_{cld} retrieval is 225.3 °K which corresponds to an altitude of 9.6 km, roughly the lidar mid-cloud height. The pixel-scale *D* and τ retrievals are shown in Figures 1b and 1c, respectively. The mean *D is* 36 µm and ranges from 30 to 90 µm. On average, $\tau \sim 2.0$, ranging from 1.0 to 4.0.

A time series of satellite-derived z_c from April 13 - 16, 1995, is shown in Figure 2 with the lidar-derived cloud boundaries. The LBTM result is shown during the daytime and both the 3-channel and IRONLY results are given at night. Correspondence between the LBTM and 3-channel

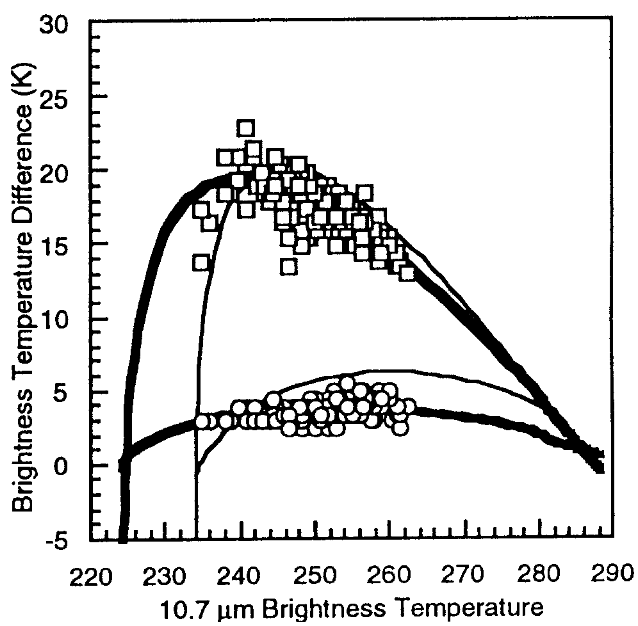

Figure 1a. Brightness temperature difference plot for cirrus cloud in a 0.5° box over the central facility at 0245 UTC on April 15, 1995.

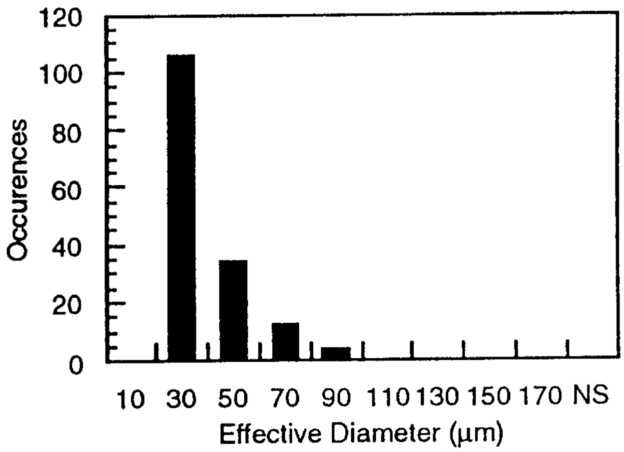

Figure 1b. Frequency of pixel-scale retrievals of D.

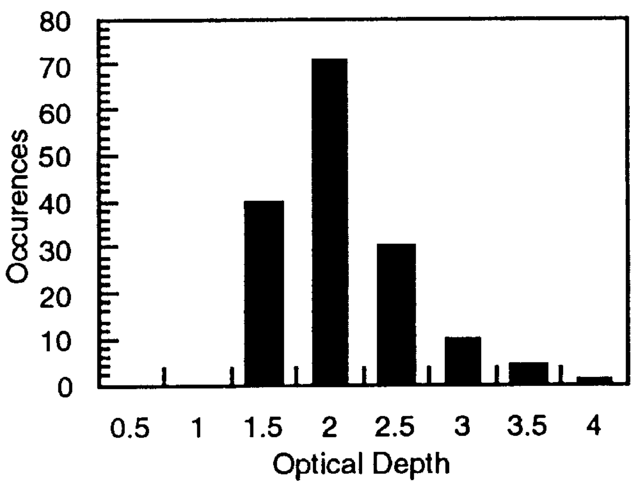

Figure 1c. Frequency of pixel-scale retrievals of τ.

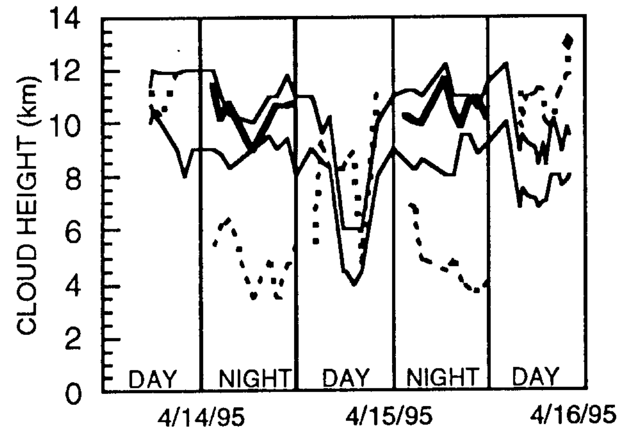

Figure 2. Cloud heights over the SCF. Lidar-derived cloud boundaries are thin solid lines; satellite-derived cloud heights are dashed (LBTM during the day, IRONLY at night) and thick solid (3-channel method) lines.

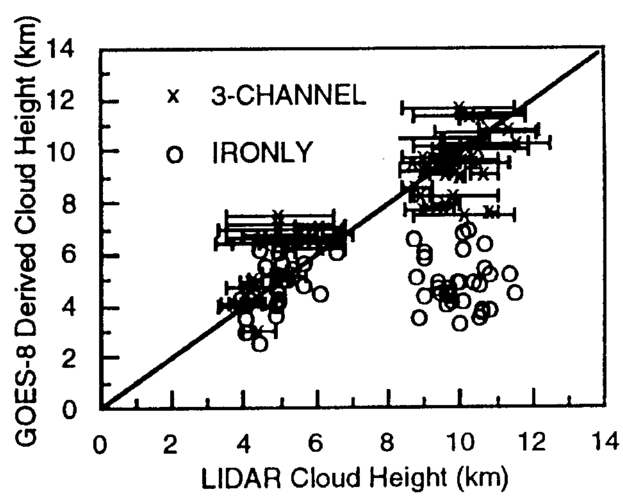

Figure 3. Comparison between cloud heights derived from GOES-8 and MPL data.

retrievals with the lidar data is excellent, while the IRONLY method results in z_c errors greater than 4 km. Figure 3 shows a comparison of the satellite- and lidar-derived cloud heights for the period when GOES-8 data were available. The results indicate that the 3-channel method agrees well (0.1 ± 1.2 km) with the lidar data, while IRONLY significantly underestimates cloud height (-3.1 ± 4.0 km).

Daytime, optically thin, high-cloud height retrievals from LBTM were extensively tested against the lidar data. The comparison shown in Figure 4 indicates that z_c(LBTM) is 0.4 ± 2.2 km higher than the lidar cloud heights. If we select only those cases with total cloud amounts greater than 80%, the difference between the LBTM and lidar heights reduces to 0.1 ± 1.1 km as found by Minnis et al. (1993).

Discussion and Conclusions

The 3-channel algorithm developed to retrieve the altitude of thin clouds at night agrees well with lidar-derived cloud heights and is a significant improvement over the IRONLY method. The derived ice-crystal sizes are comparable to those from daytime retrievals. Validation of the particle sizes will require in situ and cloud radar measurements. Because the corrected cloud heights are so close to the lidar values, it may be concluded that the τ is relatively accurate.

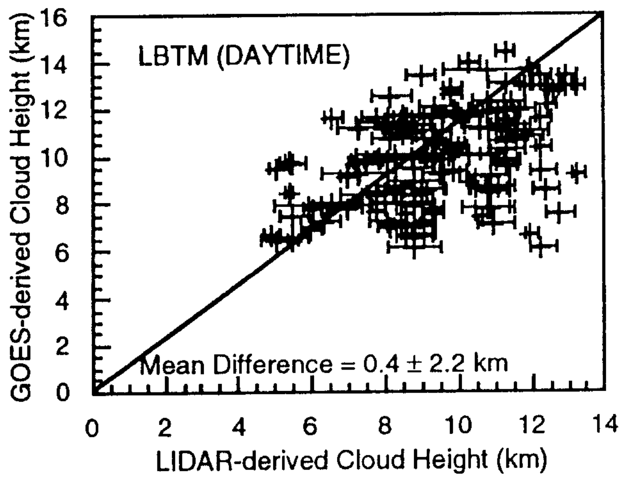

Figure 4. Comparison of high thin cloud heights derived from GOES with MPL cloud height estimates.

This new technique was applied only to single-layer cases using clear-sky temperatures determined interactively. Implementation of this method in a fully objective environment will require considerable effort to provide estimates of multi-spectral clear-sky temperatures and to detect and characterize multi-level clouds.

The comparison between the daytime LBTM and lidar cloud height retrievals (Figure 4) was reasonable although the scatter in the differences is greater than expected. A primary reason for the increased uncertainty in the cloud heights was noted earlier—the effects of partial cloud cover in rather large GOES pixels. To examine this effect, the rms differences between the lidar- and satellite-derived cloud heights were computed as a function of cloud fraction. The rms difference was nearly twice as large for cloud fractions less than 50% than it was for cloud amounts greater than 80%. If a pixel is not completely cloudfilled, the retrieved height will generally be lower than expected. Furthermore, in the case of broken and scattered clouds, the assumption of plane-parallel radiative transfer may be inoperative because brightly lit and shaded sides are conditions that are inconsistent with the models. In future comparisons of lidar and satellite cloud heights, it is desirable to examine the differences as a function of cloud amount, brokenness, and number of layers.

In addition to the partial cloud effects, the underestimates may be due to inadequately matching the lidar and satellite data in time and space, particularly when the cloud height gradient is steep or when broken, multi-level clouds occur.

Generally, we avoided comparing heights when the lidar indicated more than one cloud layer; however, we included points when the lidar indicated variable cloud height. Errors in the lidar cloud heights may be significant because the altitudes were estimated graphically from relatively small images of the lidar returns. Thus, there may be some time mismatches that become especially important in highly variable cloud fields. There also may be some cases when the lidar beam did not penetrate through the entire cloud. In these instances, the LBTM may yield a higher cloud top because the true top of the cloud is above the highest lidar return. An automated method for detecting a saturated return in the lidar signal would aid in the discrimination of the partially penetrated cloud layers.

Another source of uncertainty results from the magnitude of the clear versus cloudy thresholds assumed in the LBTM. We use a 5 °K temperature threshold which could result in the misidentification of very thin cirrus as clear, which in turn would cause an overestimate of optical depth and an underestimate in the satellite-derived cloud altitude. Other sources for uncertainty in the satellite-derived heights include errors in the clear-sky reflectance and temperature estimates and visible reflectance parameterization errors for very thin clouds. Because cirrus clouds can be composed of a variety of crystal sizes and shapes, the assumption of a single particle size and shape in the LBTM retrieval will cause some errors in the retrieved optical depth and subsequent height corrections.

The results presented here represent the first attempt to validate satellite-based cloud heights with operational ARM data. The ARM MPL is a valuable resource that will be used in a more comprehensive study of satellite-derived cloud heights and in the continued development of improved space-based n cl retrieval schemes.

References

Minnis, P., P.W. Heck, and D.F. Young, 1993: Inference of cirrus cloud properties from satellite observed visible and infrared radiances. Part Il: Verification of theoretical radiative properties, *J. Atmos. Sc*i., **50**, 1305-1322.

Minnis, P., W.L. Smith, Jr., D.P. Garber, J.K. Ayers, and D.R. Doelling, 1995a: Cloud properties derived from GOES-7 for the spring 1994 ARM Intensive Observing Period using Version 1.0.0 of the ARM Satellite Data Analysis Program. *NASA RP 1366*, August, 59 pp.

Minnis, P., O.P. Kratz, J.A. Coakley, Jr., M.D. King, R. Arduini, D.P. Garber, P.W. Heck, S. Mayor, W.L. Smith, Jr., and D.F. Young, 1995b: Cloud optical property retrieval (Subsystem 4.3). CIouds 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. December, pp. 135-176.

Acknowledgments

This research was conducted under Interagency Transfer Agreement ITF #214216AQ1 between NASA and the U.S. Department of Energy through Battelle Pacific Northwest National Laboratory.