Progress report (May 2000–August 2001)
Validation of Cloud Optical Depths Retrieved from EOS/MODIS Data

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Summary

The main purpose of this project is to contribute to the validation of operational MODIS cloud optical depth retrievals by estimating the errors that horizontal cloud variability introduces into the retrievals. The goal is to develop a technique that can give information on retrieval accuracy even at locations where no ground-based or in-situ measurements are available. The techniques setting error bounds on the inferred optical thickness values are developed through combining theoretical simulations of 3D radiative transfer with analysis of ground-based and satellite measurements.

During the past year, our research focused on the following issues:

- Improving the quality of our theoretical simulations.
- Completing an algorithm that estimates retrieval uncertainties based on the statistical distribution of 3D radiative effects in theoretical simulations.
- Developing a technique that improves the error estimates by examining spatial patterns in multi-spectral and multi-resolution MODIS observations.
- Estimating the frequency of significant retrieval uncertainties in various sets of MODIS images caused by 3D radiative effects.

Cahalan, Davis, and Wiscombe do not require funding from this project. During the past year, Marshak spent 20% of his time on the project, and Várnai worked on it almost full time (around 90%). More project-related information can be found at the project web site at http://climate.gsfc.nasa.gov/~marshak/Validation.html.

1. Introduction

First we briefly discuss what we mean by 3D radiative effects, and how they can influence the accuracy of satellite retrievals of cloud properties. Current satellite retrieval algorithms are based on 1D radiative transfer theory, which assumes that local cloud properties fully determine the brightness measured at a given pixel. This means that the retrievals do not account for the horizontal flow of radiation between areas with different properties that modify the measured radiance values, preventing the one-to-one relationships between cloud optical thickness and reflectivity. For example, 1D retrievals can significantly overestimate the optical thickness in areas that appear too bright because they are tilted toward the sun, and they can underestimate it in areas that are too dark because they are shadowed by a thicker cloud element. Moreover, significant 3D effects change not only the results for individual pixels, but also distort the overall structure of the retrieved cloud fields: they make entire scenes appear too thin or too thick, too smooth or too structured, and introduce artificial anisotropy and asymmetry into the retrieved scenes (e.g., Várnai 2000, Várnai and Marshak 2001a,b).

2. Advances during the past year

2.1 Improving the quality of theoretical simulations

In order to ensure that our radiative transfer models are accurate, we have participated in the Intercomparison of Three-Dimensional Radiation Codes (I3RC) project. The results from the two completed phases of this project indicate that our models are accurate. In addition, we made two advancements in the algorithms that specify the cloud structures used in the theoretical simulations. First, we can now specify the correlation coefficient between the cloud optical and geometrical thicknesses as a new input to our fractal cloud model. Second, we developed a test that provides further information on whether the fractal cloud fields cause realistic 3D radiative effects.

2.2 Estimating the uncertainties of MODIS retrievals

During the past year we completed the development of a technique that sets error bounds on the retrieved optical thickness values based on theoretical results on the distribution of 3D radiative effects (Várnai and Marshak 2001a). We then moved to developing a more advanced method that takes advantage of more information MODIS provides about the clouds, and estimates not only the magnitude, but also the sign of 3D radiative effects (Várnai and Marshak 2001b). The method estimates 3D effects based on the expectation that if 3D effects are important in an area, side illumination and shadowing effects should make pixels with cloud tops tilted toward the sun systematically brighter than pixels tilted away from the sun. If, on the other hand, 1D theory is adequate in an area, the two kinds of pixels should have statistically similar 0.86 μm reflectances. The sloping of the cloud top surface is estimated by examining the 11 μm brightness temperatures observed at the pixel's neighbors in front and behind, and by considering that temperature tends to decrease with altitude.

Figure 1 demonstrates the results of applying the above technique for two sets of 10 granules of MODIS data selected randomly from November 2000. It shows that the simple separation of the two kinds of pixel slopes does not reveal significant 3D effects for high sun (except for the brightest/thickest areas), but indicates abundant 3D effects for oblique sun. The figure also indicates that 3D effects have similar influences on the observed reflectances and on the optical thickness values that are retrieved from these reflectances.

The effects illustrated above were used to develop the more advanced uncertainty algorithm as follows. First, the algorithm establishes local statistical relationships between the local gradients of 11 μm brightness temperatures and the observed 0.86 μm reflectance. The algorithm then uses these local relationships to provide a first-guess estimate of 3D effects for each $(1\ \text{km})^2$ pixel. These estimates are then refined using empirical relationships obtained from theoretical simulations of the observed 3D effects. Finally, the estimated influence of 3D effects on reflectances is translated into corresponding uncertainties in the operational cloud optical thickness retrievals. Figure 2 shows an example for the τ–retrieval errors estimated for a sample scene.

Unfortunately, the method described above does not work if the sun is very high, because in this case the direction of the cloud top slope cannot make a difference in the pixels' illumination. In such cases we estimate the effects of cloud heterogeneity on 1 km-resolution retrievals from the magnitude of subpixel variability. First, we build local look-up tables that relate the observed 1 km-resolution reflectances to the retrieved

τ–values, and then we apply these tables to retrieve τ–fields from the 250 m resolution MODIS images. The comparison of the results obtained at two different resolutions then reveals how subpixel variability affects the 1 km-resolution cloud product. The resolution can affect even area-average values because of the nonlinear relationship between reflectance and optical thickness: The $(1\ km)^2$ average of τ-values retrieved from 250 m-resolution reflectances can be different from the optical thickness retrieved from the $(1\ km)^2$ average reflectance value. Figure 3 shows that the 1 km–resolution retrievals produce τ-histograms that are fairly close to the more accurate 250 m-resolution histograms, although, as expected, they underestimate the range of cloud variability toward the histograms' tails.

After developing these algorithms, we applied them to large sets of MODIS images in order to obtain initial statistics on the uncertainties of τ-retrievals. Figure 4 shows the cumulative histograms of the estimated effects on the area-averaged τ-values of $(50\ km)^2$ areas. The results show that the averaging over $(50\ km)^2$ areas reduces the errors significantly, although it does not remove them completely: The errors are smaller than 10% in about 90% of the examined areas. Since the errors are in opposite directions for high and low sun, we expect unbiased results for intermediate solar elevations.

2.3 Other results related to the project

- New techniques to retrieve cloud optical thickness values from ground-based (Marshak et al., 2000, Barker and Marshak, 2001) and airborne measurements (Barker et al., 2001).
- Photon diffusion theory for radiative transfer in inhomogeneous clouds (Davis and Marshak, 2001a,b).
- A new cloud property retrieval technique that accounts for cloud side illumination and shadowing effects (Oreopoulos et al., 2001a,b).

3. Ongoing research activities

During the next year we plan to continue our current work, focusing on the following areas.

- Improving the current estimates by incorporating new texture parameters of 250 m resolution MODIS images. This will be especially important for high solar elevations, for which no asymmetry can be detected between slopes facing toward and away from the sun. (For such cases we currently consider only a portion of the total cloud heterogeneity effects, the nonlinearity effect due to variability at scales between 250 m and 1 km.)
- Thoroughly testing and fine-tuning the developed algorithms. (For example, optimizing the size of the areas that are used to get local statistical relationships.) For this, we will use extensive theoretical simulations and examine a variety of MODIS images.
- Processing large sets of MODIS images in order to obtain climatologically representative statistics on the radiative effects of cloud heterogeneity, and on how these effects influence cloud optical thickness retrievals.

Project related publications (2000-2001)

Barker, H., and Marshak, A., 2001. Inferring Optical Depth of Broken Clouds Above Green Vegetation Using Surface Solar Radiometric Measurements. *J. Atmos. Sci.*, (in press).

Barker, H., Marshak, A., Szyrmer, W., Trishchenko, A., Blanchet, J.-P., Li, Z., 2001. Remote Sensing of Cloud Properties from Aircraft-based Measurements. *J. Atmos. Sci.*, (submitted, April 2001).

Davis, A., and Marshak, A., 2001a. Multiple Scattering in Clouds: Insights from Three-Dimensional Diffusion Theory. *Nuclear Sci. and Engin.*, 137, 251-280.

Davis, A., and Marshak, A., 2001b. Space-Time Characteristics of Light Transmitted Through Dense Clouds**.** *J. Atmos. Sci.*, (submitted, June 2001).

Marshak, A., Knyazikhin, Yu., Davis, A., Wiscombe, W., and Pilewskie, P., 2000: Cloud – Vegetation Interaction: Use of Normalized Difference Cloud Index for Estimation of Cloud Optical Thickness. *Geoph. Res. Lett.*, 27, 1695-1698.

Oreopoulos, L., Marshak, A., Cahalan, R., and Wen, G., 2000a: Cloud 3D Effects Evidenced in Landsat spatial Power Spectra and Autocorrelation Function. *J. Geophys. Res.* 105, 14777-14788.

Oreopoulos, L., Cahalan, R., Marshak, A., and Wen, G., 2000b: A New Normalized Difference Cloud Retrieval Technique Applied to Landsat Radiances Over the Oklahoma ARM Site. *J. Appl. Meteor.*, 39, 2305-2321.

Várnai, T., 2000: Influence of three-dimensional radiative effects on the spatial distribution of shortwave cloud reflection. *J. Atmos. Sci*., 57, 216–229.

Várnai, T., and A. Marshak, 2001a: Statistical analysis of the uncertainties in cloud optical depth retrievals caused by three-dimensional radiative effects. *J. Atmos. Sci*., 58, 1540-1548.

Várnai, T., and A. Marshak, 2001b: Observations of three-dimensional radiative effects that influence MODIS cloud optical thickness retrievals. *J. Atmos. Sci.*, (submitted, May 2001).

Conferences and Workshops with Project-Funded Presentations (2000-2001)

*Gordon Conference on Solar Radiation and Climat*e (New London, CT, June 2000)

Second International Workshops on the Intercomparison of Three-dimensional Radiation Codes (Tucson, AZ, November 2000)

Spring Meeting of the American Geophysical Union (Boston, MA, May 2001)

Conference of the International Association of Meteorology and Atmospheric Sciences (Innsbruck, Austria, July 2001)

Figures

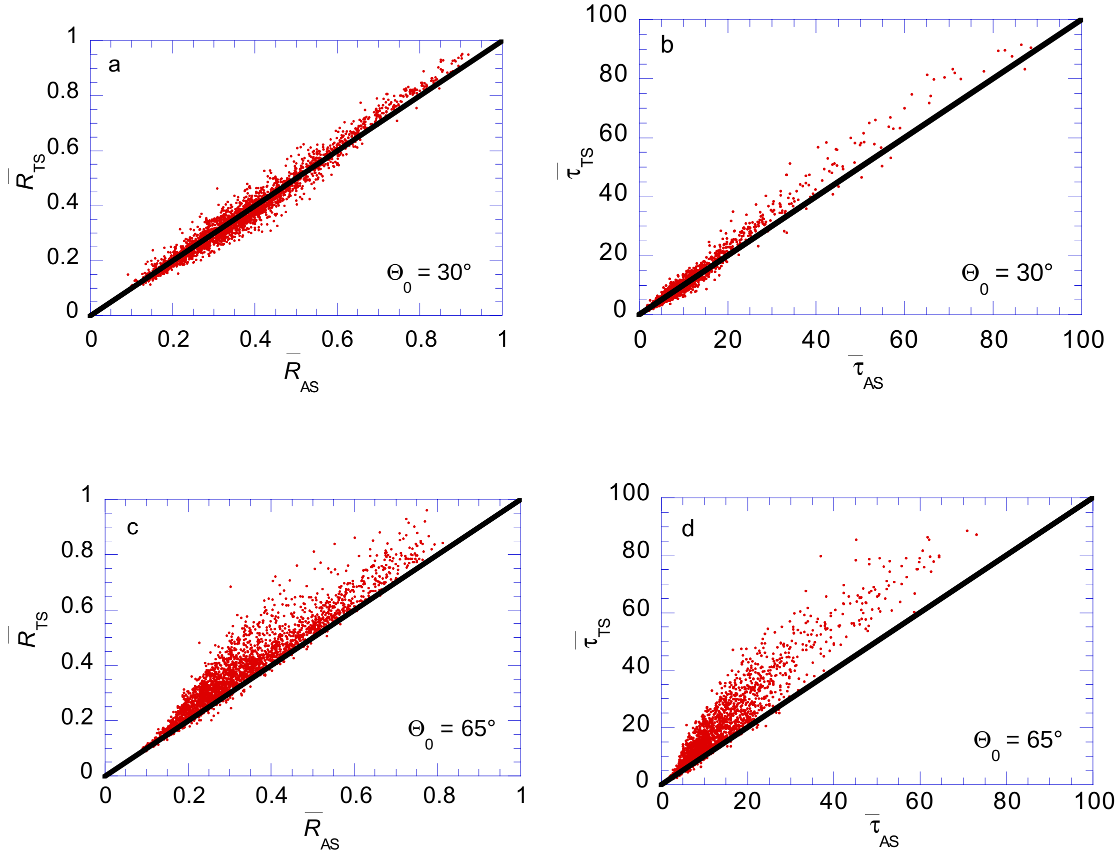

Figure 1. Comparison of (50 km)^2 area mean reflectances (R) and cloud optical thicknesses (τ) for pixels tilted toward the sun (subscript *TS*) and away from the sun (subscript *AS*). Each point represents a separate (50 km)^2 area with a cloud fraction larger than 10%. (a) Reflectance for Θ_0 = 30°; (b) Retrieved optical thickness for Θ_0 = 30°. (c) Reflectance for Θ_0 = 65°; (d) Retrieved optical thickness for Θ_0 = 65°.

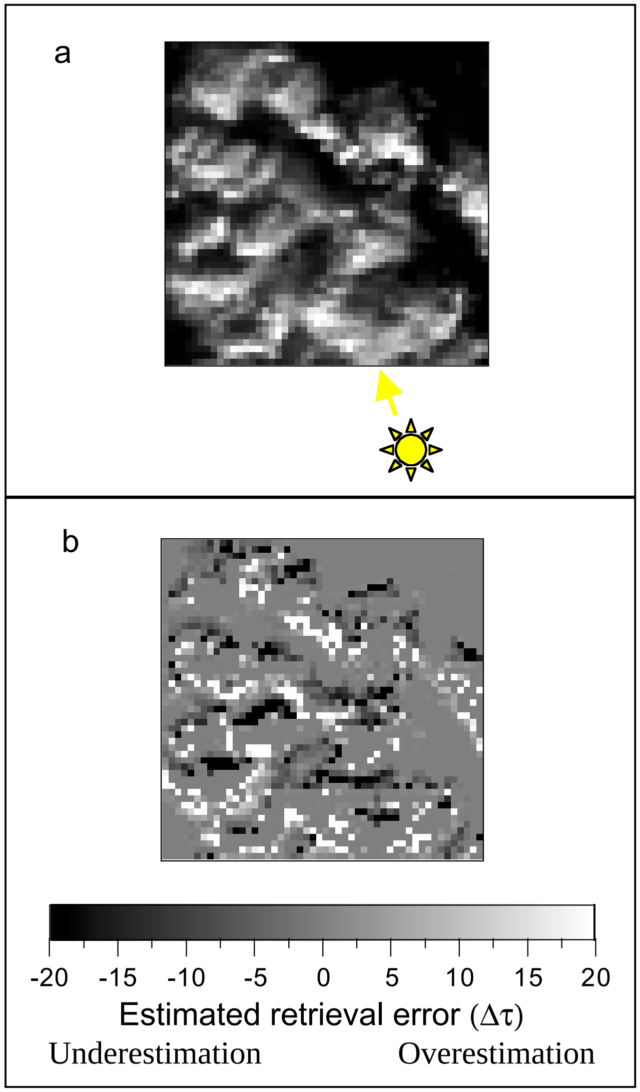

Figure 2. (a) A sample $(51\ \text{km})^2$ cloud field over the North Atlantic ocean (in the granule observed at 13:05 UTC on November 1, 2000) for Θ_0 = 75°. The cloud fraction is 78%, and the average cloud optical thickness is 39. (b) The estimated influence of 3D effects on 1 km–resolution τ–retrievals.

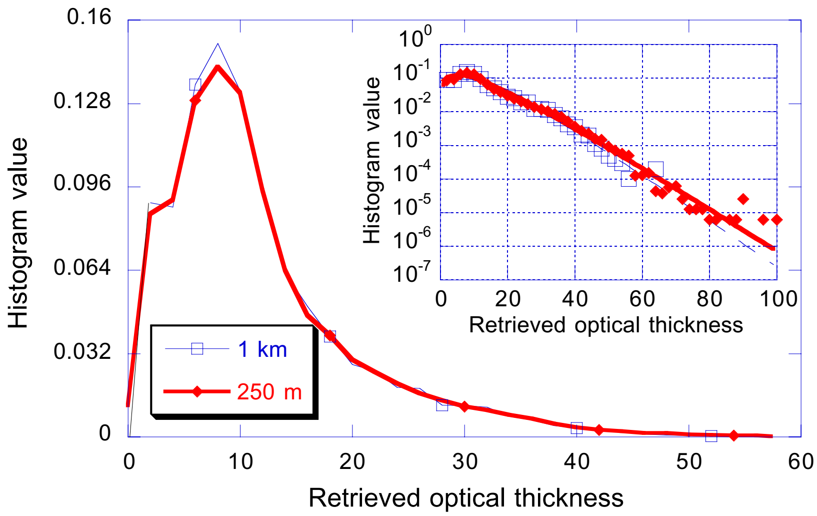

Figure 3. Comparison of the histograms of optical thickness values retrieved at 250 m– and 1 km–resolution over a sample area that contains a broken cumulus field. The cloud fraction is 90%, and the solar zenith angle is 33°. The inset shows the histograms on a logarithmic scale, which is more suitable for examining the histograms' wings at large τ values. The filled diamonds and empty squares show results for 250 m– and 1 km–resolutions, respectively. The values for 1 km–resolution drop to 0 around τ = 65, whereas the tail of the 250 m distribution reaches much further. In the inset, the solid and dashed lines display Gamma distributions fit to the 250 m– and 1 km–resolution data.

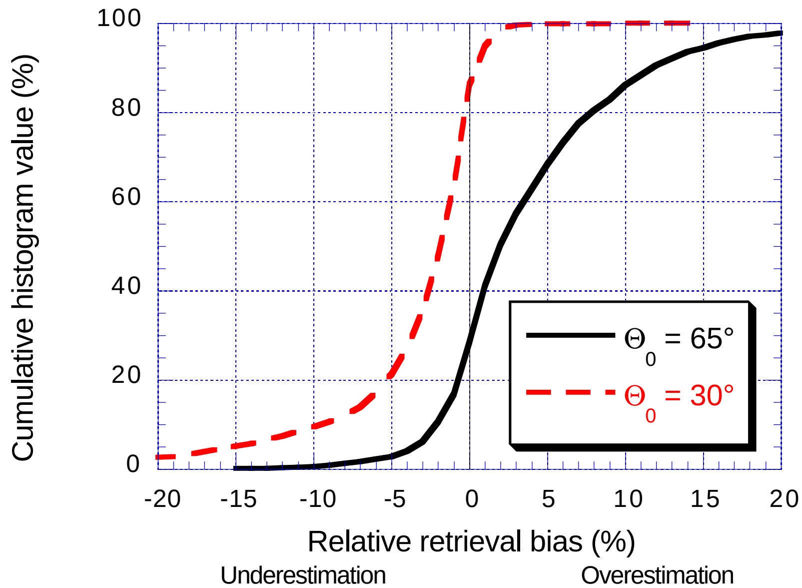

Figure 4. Cumulative histogram of estimated retrieval bias (RB) for the mean optical thickness of $(50\ \text{km})^2$ areas. Cumulative histogram is defined as the probability that for any randomly chosen area, the bias is between $-\infty$ and RB.