6.3

MODIS OBSERVATIONS ON THE OCCURRENCE OF 3D RADIATIVE EFFECTS IN CLOUDS

Tamás Várnai* and Alexander Marshak

Joint Center for Earth System Technology, University of Maryland Baltimore County,
Baltimore, Maryland

1, INTRODUCTION

Satellite measurements of the sunlight reflected by clouds are often used to retrieve various cloud properties such as optical thickness or particle size. Current methods of retrieving these cloud properties rely on one-dimensional (1D) radiative transfer theory, which implies that they cannot consider the horizontal interactions among areas that have different cloud properties. Theoretical studies have long suggested that not considering three-dimensional (3D) interactions can introduce significant uncertainties into the 1D retrievals. Satellite observations confirmed that 3D effects really are important in the interpretation of high-resolution measurements (e.g., Marshak et al. 1995), and in the cases of highly oblique solar or viewing directions (e.g., Loeb and Davies 1996; Buriez et al. 2001). This study analyzes 1 km–resolution MODIS (Moderate Resolution Imaging Spectroradiometer) images in order to find out how often 3D effects are important for moderate resolutions and sun–view geometries.

2. DATA

The presented analysis used MODIS images from March 14, 20, 27, 2001, and from September 14, 20, 27, 2001. For each day, we selected the 20 image segments (called granules) whose center was closest to 45° North and 45° South latitudes, yielding 120 granules. In order to avoid complications that may arise at very oblique view directions, we used only the central portion of each granule, which covered 2000 km long and 450 km wide areas. The analysis ingested the 1 km–resolution radiances measured at 0.86 μm, 2.12 μm, and 11 μm wavelengths, as well as the cloud optical thickness and particle size values from the operational MODIS cloud product. Because the sun is near the equator in September and June, the solar zenith angle at the center of the images was around 50°, and ranged mainly between 40° and 60° at the edges of the images.

3. METHODOLOGY

The influence of 3D effects was detected in the satellite data using the technique described in Várnai and Marshak (2002a). This technique divides the satellite images into 50 km by 50 km areas, and examines all cloudy pixels in each area (i.e., all pixels for which the operational MODIS data processing retrieved a non-zero cloud optical thickness—regardless of cloud phase or location). The cloudy pixels in each area are separated into two categories depending on whether 3D effects are expected to enhance or reduce the pixels' shortwave reflectance. The mean properties of the two categories are then compared to one another in order to estimate how big a difference 3D effects make—i.e., how important 3D effects are.

In the adopted approach, the main sources of brightness enhancements and reductions are changes in the solar illumination if the cloud top surface is not horizontal, but is tilted toward or away from the sun. The direction of the slope at a particular pixel is determined in two steps. Step 1 determines which two neighboring pixels in front and behind are closest to the solar azimuth. Step 2 then compares the 11 μm brightness temperatures of these two neighbors. Because temperature generally decreases with altitude, the technique assumes that our pixel is on a slope tilted toward the sun if $T_{front} > T_{behind}$ and that it is on a slope tilted away from the sun if $T_{front} < T_{behind}$.

*Corresponding author address: Tamás Várnai,
Code 913, NASA GSFC, Greenbelt, MD, 20771
email: varnai@climate.gsfc.nasa.gov

4. RESULTS

Our first test compared the mean 11 μm brightness temperatures calculated for the pixels in slopes facing toward and away from the sun, respectively (Fig. 1). The results indicate that although random effects such as wind shear can make clouds asymmetric in individual (50 km)^2 areas, the slopes facing toward and away from the sun tend to have very similar brightness temperatures. (If anything, the data reveals a minimal asymmetry that clouds are colder by 0.1°C at the slopes facing away from the sun.) This means that clouds don't grow systematically taller on their slopes facing toward the sun—and so if clouds appear systematically brighter in these slopes, the difference can be attributed to 3D radiative effects with great confidence.

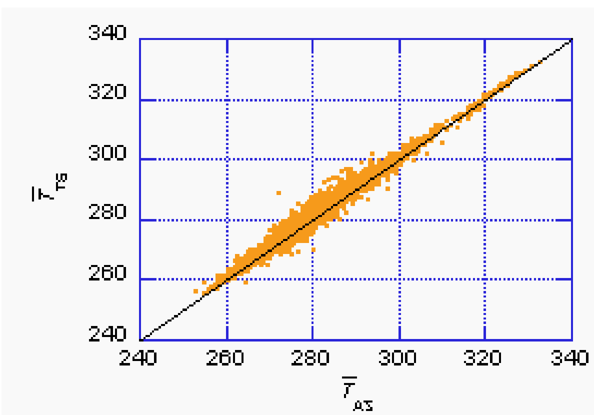
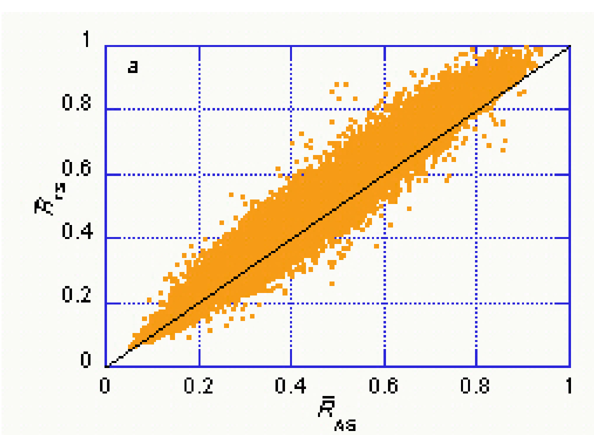


Figure 1. Comparison of the mean 11 μm brightness temperatures of slopes facing toward the sun (*TS*) and away from the sun (*AS*). Each dot represents the mean values for an individual (50 km)^2 area.



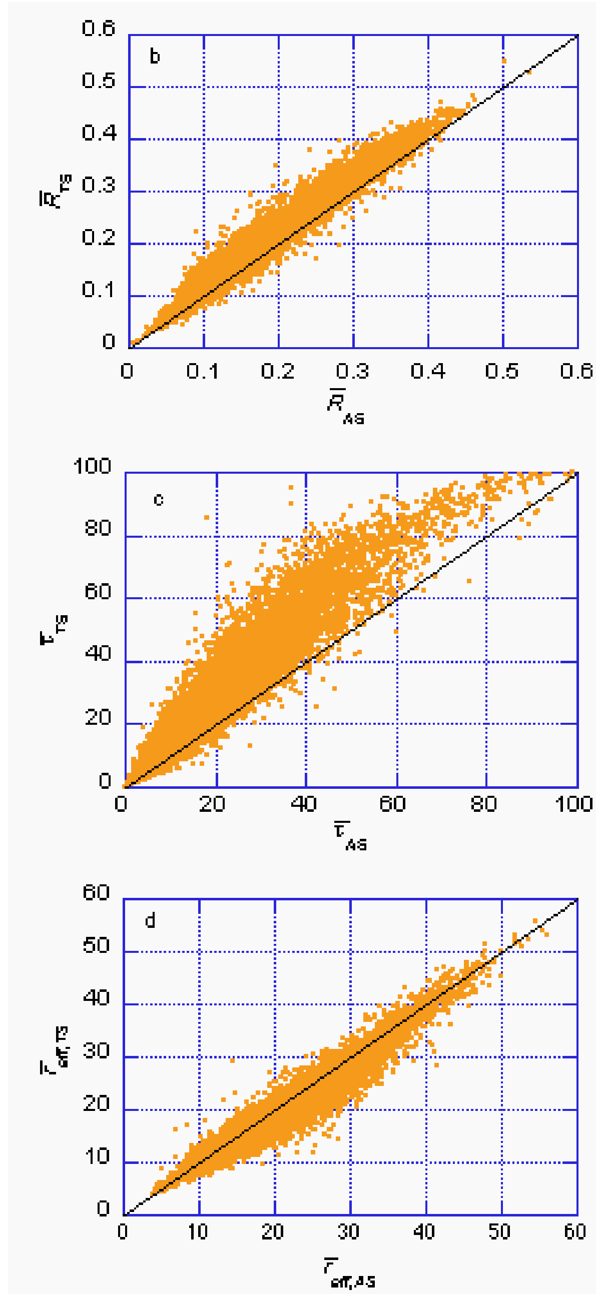


Figure 2. Comparison of mean reflectances and retrieved cloud properties at slopes tilted toward and away from the sun. (a) 0.86 μm reflectance; (b) 2.12 μm reflectance; (c) cloud optical thickness; (d) cloud particle size.

Next, we compared the shortwave reflectances measured over the two kinds of slopes, and also the cloud properties that were retrieved at these slopes (Fig. 2). The results reveal that slopes facing the sun appear systematically brighter in satellite images, which is a clear indication of significant 3D radiative effects.

Let us note that the asymmetry of reflectance fields is slightly larger at 2.12 μm than at 0.86 μm. This tendency agrees well with theoretical considerations: the absorption at 2.12 μm reduces the amount of diffuse radiation that can make its way from illuminated to shadowy slopes, and this reduction enhances the brightness difference between the two kinds of slopes.

Figure 2 also reveals that the asymmetry of reflectance fields results in retrievals of artificially asymmetric cloud fields: the 1D retrievals assume that the slopes facing the sun are brighter because clouds have larger optical thicknesses there. (The calculated water path fields display similar asymmetries.) As Panel d shows, however, the retrievals of cloud particle size are less influenced by 3D effects. This is because 3D effects usually change the reflectances at 0.86 μm and 2.12 μm in a similar way, and the effects at the two wavelengths tend to cancel out each other in particle size retrievals (Várnai and Marshak 2002b). One can also note that the influence of 3D effects goes in the other direction for particle size than for optical thickness: the retrieval procedure (Nakajima and King 1990) yields larger values on the slopes facing away from the sun.

In order to get quantitative information on the frequency of 3D radiative effects, let us calculate for each (50 km)^2 area the absolute difference (*AD*) and the relative difference (*RD*) between the mean optical thickness value of the two kinds of slopes:

$$AD = \bar{\tau}_{TS} - \bar{\tau}_{AS} \quad (1)$$

$$RD = \frac{\left(\bar{\tau}_{TS} - \bar{\tau}_{AS}\right)}{\left(\frac{\bar{\tau}_{TS} + \bar{\tau}_{AS}}{2}\right)} 100\% \quad (2)$$

The cumulative histogram (*CH*) of the absolute differences reveals that in most cases the absolute differences are not too large: they are less than 10 in 90% of the (50 km)^2 areas (Fig. 3a). But if we look at the differences in relative terms, they appear much more substantial: for example, the median value is 16% relative difference (Fig. 3b).

In considering how the solar zenith angle influences the asymmetries (i.e., the magnitude of detected 3D effects), one could expect that the asymmetries increase substantially for more and more oblique sun, as the slopes facing the sun capture more and more of the incoming solar radiation. Figure 4 clearly shows an increase, although a fairly modest one. The main factor mitigating the increase is probably that in MODIS images more oblique sun occurs closer to the poles—where clouds tend to be less convective, containing more gradual slopes.

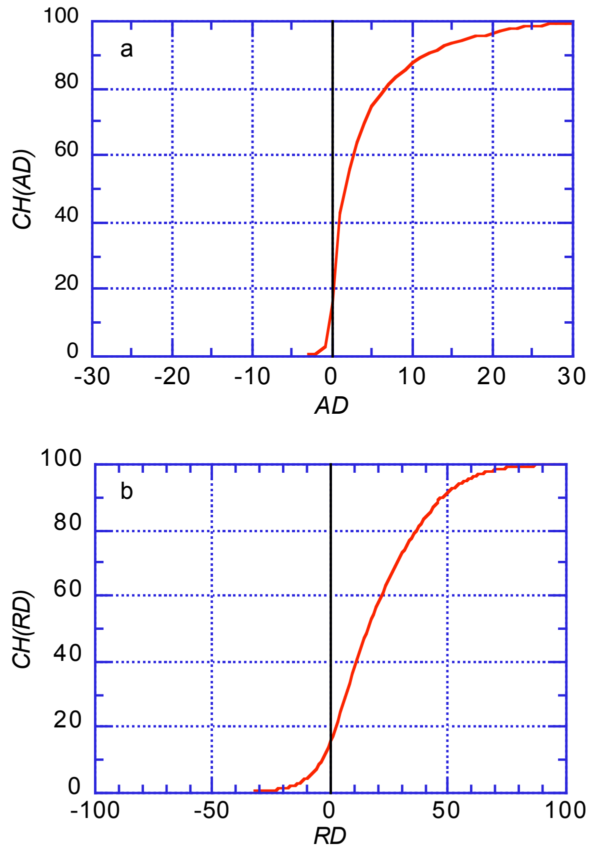


Figure 3. Cumulative histogram (*CH*) of the (a) *AD* and (b) *RD* values calculated for each (50 km)^2 area. The cumulative histogram is defined as the probability that, for any randomly chosen area, the difference *AD* (or *RD*) lies between -∞ and *AD* (or *RD*).

Because 3D effects cause errors in 1D retrievals in a such way that the errors have opposite signs at the slopes facing toward and away from the sun, one may wonder whether one could avoid the errors by simply averaging the retrieval results over larger areas. This averaging could help because the larger areas could encompass slopes facing both toward and away from the sun, and so the counteracting errors could cancel out each other. Figure 5 shows that spatial averaging really reduces the influence of 3D effects, but also that the reduction is fairly gradual. The figure suggests that averaging over at least 20 or 30 km would be needed to eliminate the asymmetries caused by 3D effects. Let us note, however, that even large-scale averaging could not eliminate the other consequences of 3D effects, such as the changes in area average values observed by Loeb and Davies (1996).

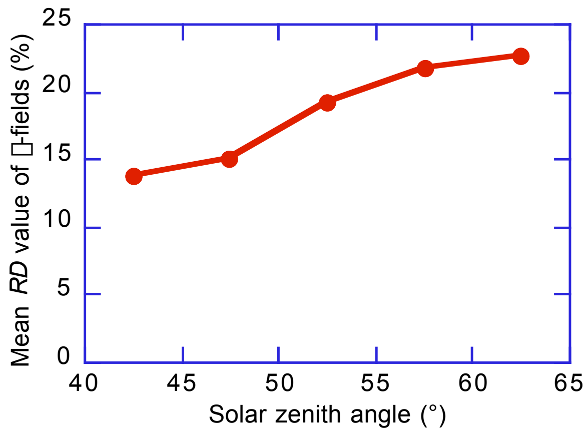


Figure 4. Solar zenith angle dependence of the mean *RD* value.

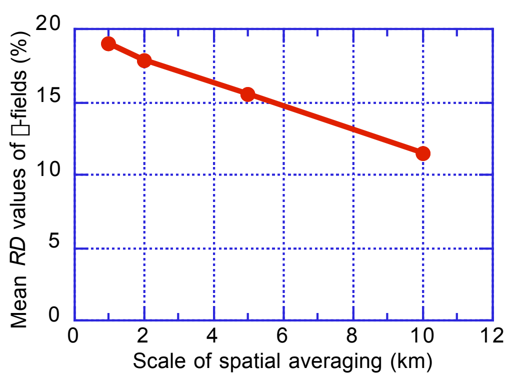


Figure 5. Reduction in *RD* values if the optical thickness retrieval results and the 11 µm brightness temperature values are averaged over large scales.

5. CONCLUSIONS

The presented study analyzed 1 km–resolution MODIS images to examine the influence of 3D radiative interactions on shortwave cloud reflectance and on satellite retrievals of cloud properties. The main findings were as follows:

• 3D radiative effects have a well-pronounced influence in a majority of cloud fields: They make clouds appear asymmetric in visible and near-infrared satellite images, and they cause retrievals of artificially asymmetric optical thickness and water path fields. (In contrast, the influence on cloud particle size retrievals is less pronounced.)

• The magnitude of the detected 3D effects increases slightly with the solar zenith angle.

• The asymmetries caused by 3D radiative effects remain significant even if the retrieval results are averaged over intermediate scales (in the order of 10 km).

Because even large-scale averaging can avoid only the asymmetry but not the other consequences of 3D effects, the results indicating an abundance of strong 3D interactions highlight the need for new approaches in the interpretation of satellite measurements.

Acknowledgements: This research is supported by the NASA EOS Project Science Office under grant NAG5-6675.

REFERENCES

Buriez, J.-C., M. Dutriaux-Boucher, F. Parol, and N. G. Loeb, 2001: Angular variability of the liquid water cloud optical thickness retrieved from ADEOS-POLDER. *J. Atmos. Sci.*, **58**, 3007-3018.

Loeb, N. G., and R. Davies, 1996: Observational evidence of plane-parallel model biases: Apparent dependence of cloud optical depth on solar zenith angle. *J. Geophys. Res.*, **101**, 1621-1634.

Marshak, A., A. Davis, W. Wiscombe, G. Titov, 1995: The verisimilitude of the independent pixel approximation used in cloud remote sensing. *Remote Sens. Eviron.*, **52**, 71-78.

Nakajima, T. Y., and M. D. King, 1990: Determination of the optical thickness and effective radius of clouds from reflected solar radiation measurements. Part I: Theory. *J. Atmos. Sci.*, **47**, 1878-1893.

Várnai, T., and A. Marshak, 2002a: Observations of three-dimensional radiative effects that influence MODIS cloud optical thickness retrievals. *J. Atmos. Sci.*, **59**, 1607-1618.

Várnai, T., and A. Marshak, 2002b: Observations of three-dimensional radiative effects that influence satellite retrievals of cloud properties. *Idojárás* (*Quarterly Journal of the Hungarian Meteorological Society*). **106**, 265-278.