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Validation of Cloud Optical Depths Retrieved from EOS/MODIS Data

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Summary

The main purpose of this project was 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 was to develop a technique that can give information on retrieval accuracy even at locations where no ground-based or in-situ measurements are available.

Prior to the launch of MODIS on board the Terra satellite, we used radiative transfer simulations to study the effects of cloud variability and to develop simple parameterizations of the uncertainties they introduce into cloud property retrievals. After MODIS data became available in 2000, we focused on the statistical analysis of MODIS observations, both for improving the methods that estimate retrieval uncertainties and for examining the magnitude of the uncertainties cloud variability causes in the real atmosphere.

The main achievements of the project are:

- Development of the first algorithms that estimate retrieval uncertainties caused by cloud heterogeneity effects;
- New knowledge on the importance of cloud variability in the real atmosphere;
- New insights into the radiative effects of cloud variability, which can help improve future cloud retrieval algorithms.

Results from the project were published in 12 journal articles (one more is under preparation), were discussed in 14 conference presentations, and were informally reported to MODIS team members who used them to improve the current operational algorithms.

Introduction

Here we briefly discuss what the radiative effects of horizontal cloud variability are, and how they influence the accuracy of satellite retrievals of cloud properties. Current satellite retrieval algorithms are based on one-dimensional (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 three-dimensional (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. Finally, the nonlinearity of the 1D relationship between cloud properties and corresponding 1D radiances means that subpixel variability can cause additional biases (so-called plane-parallel bias) even in the framework of 1D radiative transfer.

Description of work

Radiative transfer modeling

We started the project by setting up an integrated simulation system that automatically creates hundreds of artificial but realistic cloud fields, calculates the reflectivity of randomly selected areas in these scenes, and performs hypothetical satellite retrievals for the simulated areas. The simulation system made it easy to obtain and analyze statistically representative results for a wide variety of cloud fields.

As part of this development we adapted some of the best stochastic cloud models to date and improved them to produce more realistic histograms, autocorrelation functions and to ensure prescribed correlations between various cloud properties (e.g., optical and geometrical cloud thicknesses). In order to check the quality of our Monte Carlo radiative transfer models, we have participated in the Intercomparison of Three-Dimensional Radiation Codes (I3RC) project supported by NASA Radiation Sciences and DoE's ARM programs (http://i3rc.gsfc.nasa.gov). Results from the first two phases of this project confirm the accuracy of our radiative transfer models.

Theoretical estimates of retrieval uncertainty

Until MODIS data became available following the launch of Terra, we used our simulation system to perform theoretical investigations on the influence of cloud variability. As an example, Fig. 1 shows the histogram of true optical thicknesses of pixels whose simulated reflectances are identical. Because 1D retrievals assume a one-to-one relationship between optical thickness and nadir reflectance, 1D retrievals yield identical optical thicknesses for all pixels in each of the three groups. Thus the spread of true optical thicknesses in Fig. 1 indicates the spread of 1D retrieval errors. The figure reveals that retrieval uncertainties tend to increase with the observed reflectance, and that the error distributions are skewed—implying that different error bars should be used for underestimations and overestimations. Based on such statistical results we proposed a simple parameterization that can give first-order estimates of the retrieval uncertainties caused by 3D radiative effects.

Retrieval uncertainties based on the analysis of MODIS data

After Terra's launch, the focus of our research has been shifted to the statistical analysis of MODIS observations. Our analysis combined visible and infrared data and also examined the behavior of operational MODIS retrieval products of cloud optical thickness, effective particle size, and cloud water path.

Our basic approach started by separating pixels into two categories that have similar cloud properties but whose reflectances are influenced by 3D radiative effects in different ways. The difference between the statistical properties of pixels in these two categories then indicated the magnitude of 3D effects. We used two methods to separate the pixels that are supposedly brightened and darkened by 3D effects.

The first technique used the 11 µm MODIS brightness temperatures to estimate the slope of the cloud top surface at each pixel, and considered that 3D effects make pixels appear brighter if they are on slopes facing toward, rather than away from, the sun. Statistical comparisons of pixels on the two kinds of slopes revealed this effect clearly, and also showed that this causes cloud retrievals to overestimate optical thickness and water content on slopes facing the sun, and underestimate them on the opposite slopes. As an example, Fig. 2 shows that, because of 3D effects, the orientation of cloud top slope has a strong influence on the retrieved water path values.

Because theoretical simulations indicated that the differences between the two kinds of slopes are closely related to other consequences of 3D radiative processes (e.g., area-averaged biases), we used the easily observable differences to examine the climatological distribution of 3D effects. A sample result is shown in Fig. 3, which indicates that 3D effects are slightly stronger over land than over ocean, with a mean relative difference of 15% between the two kinds of slopes.

In addition, we developed a new algorithm that combined large-scale asymmetries and parameters of local cloud variability to estimate the retrieval uncertainties due to 3D effects for (1 km)^2 pixels. These estimates also included information on subpixel variability, as provided by MODIS's 250 m-resolution visible images. Finally, the investigations also revealed that, in comparison to retrievals of optical thickness and water path, effective particle size retrievals were less affected, because 3D effects at visible and near-infrared wavelengths had opposite, canceling influences on the retrieved values.

Our second approach to examining the influence of 3D radiative processes was to analyze the view angle dependence of 1D retrieval results. Although ideally, the retrieval results shouldn't depend on view direction, Fig. 4 shows some clear tendencies. The similarity of behaviors at the two edges of MODIS swaths suggests that the observed tendencies are not caused by diurnal effects (cloud optical thickness is not likely to peak in the late morning), but are caused by limitations of 1D retrievals. The large number of thin clouds at swath edges may be due to more sensitive cloud detection at oblique views, but the larger number of thick clouds at the swath center is most likely due to 3D radiative effects. Our theoretical simulations, showed a similar behavior: 1D retrievals based on 3D-simulated radiances yielded larger optical thicknesses for overhead views than for oblique views.

Overall, this project yielded new insights into the mechanisms and importance of 3D radiative effects, and developed the first algorithms to estimate the uncertainties they cause in 1D cloud property retrievals. Some of our findings were used by the MODIS team to improve the quality of current operational retrieval algorithms. Finally, the results pointed out some promising new directions for future research. We recently submitted a proposal to the NASA radiation sciences program to build on the current project's results and improve our ability to consider cloud heterogeneity effects in cloud retrievals.

Project related publications

Peer reviewed journal articles

Várnai, T., and A. Marshak, 2003: A method for analyzing how various parts of clouds influence each other's brightness. Submitted to *J. Geophys. Res*.

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

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

Davis, A., and Marshak, A., 2002. Space-time characteristics of light transmitted through dense clouds**.** *J. Atmos. Sci.*, **59**, 2714-2728.

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

Davis, A., and Marshak, A., 2001. Multiple scattering in clouds: Insights from three-dimensional diffusion theory. *Nuclear Sci. and Engin.*, **137**, 251-280.

Barker, H., and Marshak, A., 2001. Inferring optical depth of broken clouds above green vegetation using surface solar radiometric measurements. *J. Atmos. Sci.*, **58**, 2989-3006.

Oreopoulos, L., Marshak, A., Cahalan, R., and Wen, G., 2000. Cloud three-dimensional effects evidenced in Landsat spatial power spectra and autocorrelation function. *J. Geophys. Res.*, **105**, 14777-14788.

Marshak, A., Oreopoulos, L., Davis, A., Wiscombe, W., and Cahalan, R., 1999. Horizontal radiative fluxes in clouds and accuracy of the Independent Pixel Approximation at absorbing wavelengths. *Geoph. Res. Lett.*, **26**, 1585-1588.

Davis, A., Marshak, A., Gerber, H., and Wiscombe, W., 1999: Horizontal structure of marine boundary-layer clouds from cm– to km–scales. *J. Geophys. Res.* **104**, 6123-6144.

Marshak, A., Davis, A., Cahalan, R., and Wiscombe, W., 1998. Nonlocal Independent Pixel Approximation: direct and inverse problems. *IEEE Trans. Geosci. Remote Sens.*, **36**, 192–205.

Marshak, A., Davis, A., Wiscombe, W., and Cahalan, R., 1998. Radiative effects of sub-mean-free-path liquid water variability observed in stratiform clouds. *J. Geophys. Res.*, **103**, 19557-19567.

Conference presentations

Observations of 3D radiative effects in MODIS cloud optical thickness retrievals. *MODIS Science Team Meeting,* Greenbelt, MD, July 22-24, 2002.

Analysis of cloud optical thickness retrieved from CIMEL measurements. *AGU Spring Meeting*, Washington DC, May 28-31, 2002.

MODIS observations on the occurrence of 3D radiative effects in clouds. *11th Conference on Atmospheric Radiation,* Ogden, UT, Amer. Meteor. Soc., 68-71, 2002.

Influence of 3D radiative effects on satellite retrievals of cloud properties. *Conference of the International Association of Meteorology and Atmospheric Sciences,* Innsbruck, Austria, 2001.

Do fractal models of clouds produce the right 3D radiative effects? *Spring Meeting of the American Geophysical Union*, Boston, MA, 2001.

Cloud structure and cloud-radiation interaction: from smallest observable scales (less than 10 m) to GCM scales (more than 100 km). *AGU Spring Meeting*, Boston, MA, June 1 - 2, 2001.

Optical depth retrieval validations for MODIS. *I3RC Workshop*, Tucson, AZ, 2000.

Analysis of how cloud portions influence each other's brightness. *Gordon Conference on Solar Radiation and Climate*, New London, CT, 2000.

A statistical analysis of the uncertainties 3D radiative effects introduce into MODIS cloud optical depth retrievals. *Gordon Conference on Solar Radiation and Climate*, New London, CT, 2000.

Error bounds for MODIS retrievals of the optical depth of horizontally inhomogeneous clouds. *EOS Investigator Working Group Meeting*, Tucson, AZ, 2000.

Three - dimensional radiative effects of cloud structure in remote sensing. *School on "Exploring the Atmosphere by Remote Sensing Techniques"*, Trieste, Italy, October 25 - 30, 1999.

Radiative effects of three-dimensional cloud structures. *Goddard Lab for Atmospheres Research MTR Presentation*, Greenbelt, MD, October 22, 1999.

Radiative smoothing in clouds at transparent and absorbing wavelengths. *AGU Spring Meeting*, Boston, MA, June 2 - 5, 1999.

Accuracy of the Independent Pixel Approximation at absorbing wavelengths. *AMS 10th Conference on Atmospheric Radiation*, Madison, WI, June 27 - July 2, 1999.

Figures

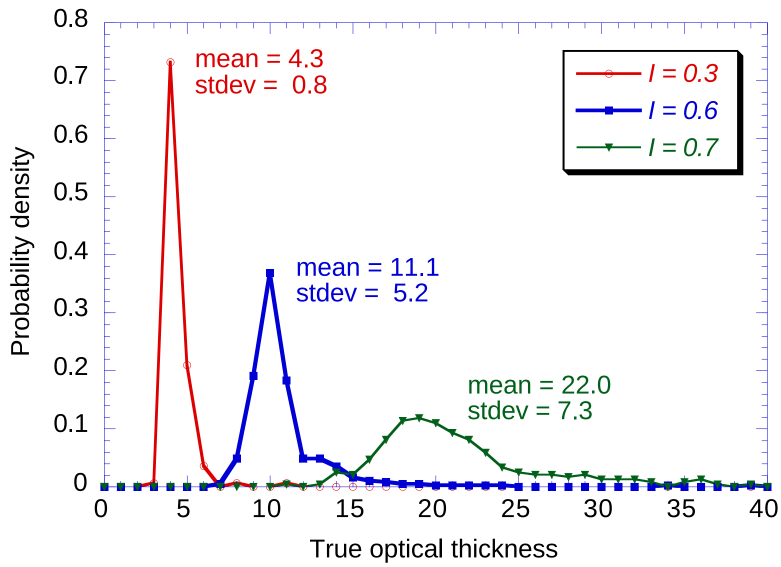

Figure 1. Histogram of true optical thickness values for pixels in various reflectivity intervals.

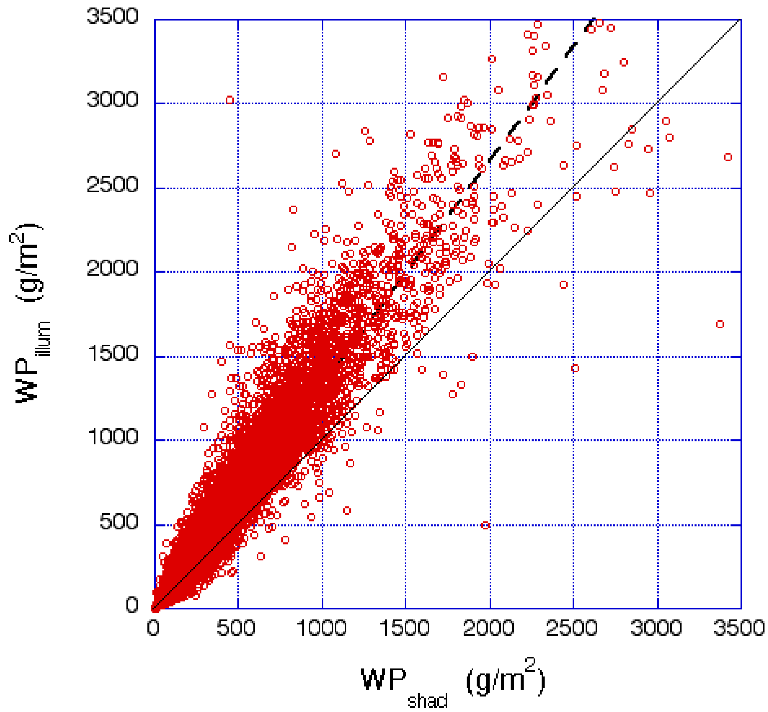

Figure 2. Comparison of mean water path (WP) values retrieved over slopes facing toward and away from the sun (WP_{illum} and WP_{shad}, respectively). Each point represents the mean *WP* values for a separate (50 km)^2 area. The figure displays all cloudy areas in 30 MODIS granules that had a cloud coverage greater than 10%. (Areas with very small cloud content were excluded to reduce statistical uncertainties.) The solar zenith angle is around 60°.

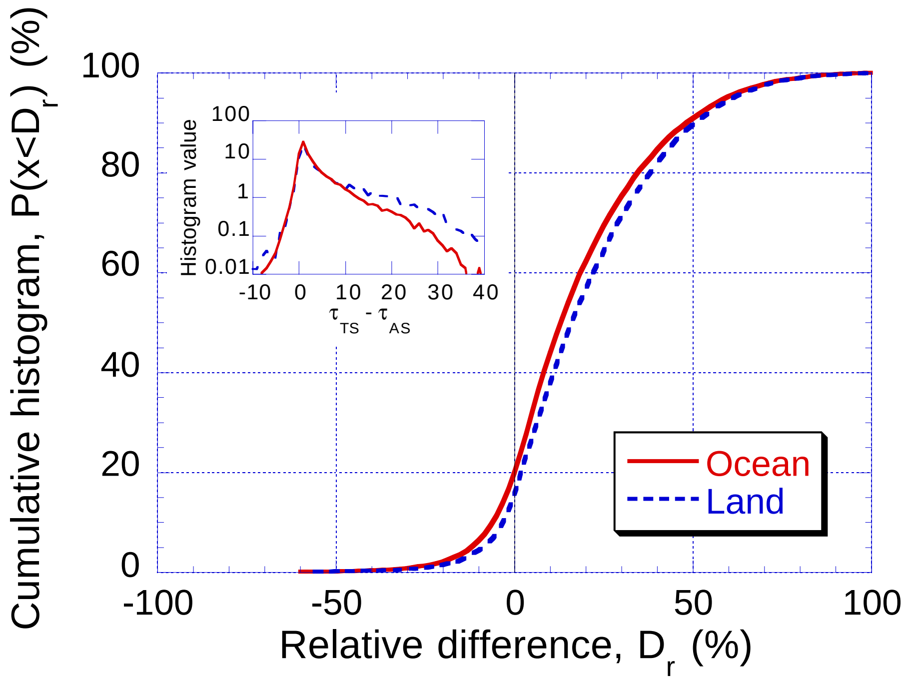

Figure 3. Comparison of (cumulative) histograms of relative difference D_r in optical thicknesses retrieved from clouds over land and ocean. The same 30 MODIS granules were used as in Fig. 2. The inset shows the histograms on a logarithmic scale of asymmetry vs. the difference between the average optical thicknesses of pixels on slopes facing toward and away from the sun (τ_{TS} and τ_{AS}, respectively).

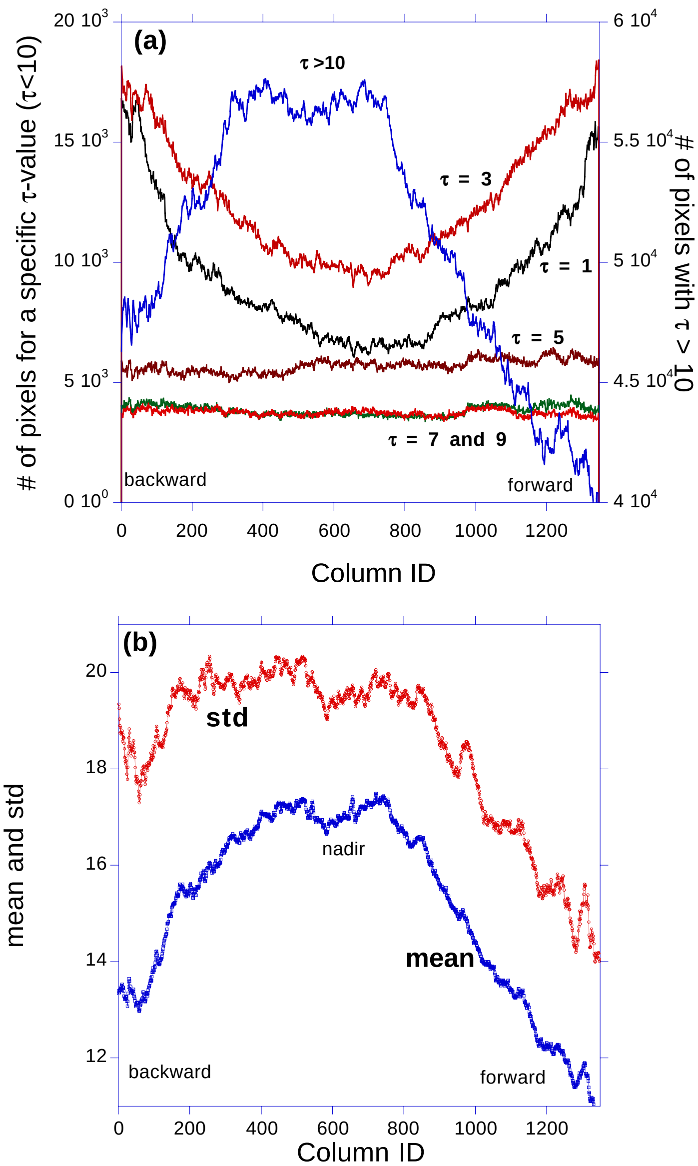

Figure 4. (a) Number of cloudy pixels and (b) mean and standard deviation of MODIS cloud optical depth vs. cross-track position (labeled "Column ID"). Each cross-track position corresponds to a different view angle: the zenith view angle changes from 0^{o} at the center to 60^{o} at the edges, while the azimuth view angle changes from 50^{o} (backward) at the left edge to 115^{o} (forward) at the right edge. These data were retrieved from 120 images in both Northern and Southern Hemispheres around 45^{o} latitude, with solar zenith angles of $51^{o}\pm7^{o}$. True cloud properties are independent of view angle, so that curves in (a) will be flat when retrievals are replaced by ones properly accounting for 3D effects.