Evidence for Three-Dimensional Radiative Effects in MODIS Cloud Optical Depths Retrieved at Back Scattering View Angles

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

Alexander Marshak
Climate and Radiation Branch, NASA Goddard Space Flight Center

Prepared for *Atmospheric Research*

Popular summary

Satellite remote sensing is such a complex task that could be done only by assuming that there are no radiative interactions between areas that have different cloud properties. It is true that some recently proposed methods consider such interactions, but these novel methods are not yet ready for operational use. As a result, researchers must continue relying on one-dimensional (1D) radiative theory, which does not include the interactions. The hope is that the neglected three-dimensional (3D) interactions do not matter much in remote sensing applications, and so current methods give accurate results.

This study addresses the question whether 1D radiative transfer theory describes well how the clouds' solar reflection depends on viewing angle. The statistical analysis of a large set of MODIS observations indicates that in oblique backward scattering directions, cloud reflection is stronger than 1D theory would predict. After considering a variety of possible causes, the paper concludes that the most likely reason for the increase lies in 3D radiative interactions. The results' main implication is that cloud optical depths retrieved at back scattering view angles larger than about 50° tend to be overestimated and should be used only with great caution.

Evidence for three-dimensional radiative effects in MODIS cloud optical depths retrieved at back scattering view angles

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

Alexander Marshak
Climate and Radiation Branch
NASA Goddard Space Flight Center

Prepared for *Atmospheric Research*

August 8, 2003

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

Abstract

This study addresses the question whether 1D radiative transfer theory describes well the angular distribution of shortwave cloud reflection. The statistical analysis of a large set of MODIS observations indicates that in oblique backward scattering directions, cloud reflection is stronger than 1D theory would predict. After considering a variety of possible causes, the paper concludes that the most likely reason for the increase lies in 3D radiative interactions. The results' main implication is that cloud optical depths retrieved at back scattering view angles larger than about 50° tend to be overestimated and should be used only with great caution.

1. Introduction

Satellite remote sensing is such a complex task that could be done only by assuming that there are no radiative interactions between areas that have different cloud properties. It is true that some recently proposed methods (e.g., Marshak et al. 1998, Oreopoulos et al. 2000, Fauré et al. 2001, Várnai and Marshak 2002) consider such interactions, but these novel methods are not yet ready for operational use. As a result, researchers must continue relying on one-dimensional (1D) radiative theory, which does not include the interactions. The hope is that the neglected three-dimensional (3D) interactions do not matter much in remote sensing applications, and so current methods give accurate results.

In recent years, several observational studies examined the validity of this hope. These studies found that, under certain conditions, 3D effects cause significant problems. Specifically, they revealed that 3D effects can make clouds appear too smooth (Marshak et al. 1995, Davis et al. 1997), too bright and thick (Loeb and Davies 1996, Loeb and Coakley 1998), and artificially asymmetric (Várnai and Marshak 2002).

While the papers above focused mainly on overhead satellite views, some studies examined 3D effects for oblique views. A comparison of GOES and Meteosat radiances for scenes that were viewed from different directions by the two satellites did not reveal any influence of 3D effects (Rossow 1989). Examining ERBE (Earth Radiation Budget Experiment), AVHRR (Advanced Very High-Resolution Radiometer), and POLDER (Polarization and Directionality of the Earth's Reflectances) data, some other studies found that for low sun, 3D interactions such as shadowing make clouds appear too dark from oblique views facing the sun, and that this makes 1D retrievals underestimate cloud optical thickness (Loeb and Davies 1997; Loeb and Coakley 1998; Buriez et al. 2001). Theoretical studies (e.g., Davies 1984; Kobayashi 1993; Várnai 2000; Iwabuchi and Hayasaka 2002) have long suggested that 3D effects have an opposite influence for oblique views facing away from the sun—but the observations cited above have not confirmed unambiguously the existence of this enhanced backscatter from sunlit slopes. Most recently, Zuidema et al. (2003) found that in highly heterogeneous cumulus congestus clouds, oblique backscatter reflectances observed by MISR (Multi-angle Imaging SpectroRadiometer) exceeded 3D radiative transfer calculations based on cloud structure retrieved from the MISR nadir camera using 1D theory.

The goal of this paper is to analyze the view angle dependence of cloud reflection and its effect on cloud optical depth retrieval. Special focus is put on the enhancement in backward scattering directions. For this, the study uses high resolution MODerate-resolution Imaging Spectroradiometer (MODIS) observations of a wide variety of cloud types. First, Sections 2 and 3 describe the data we analyzed and the methodology we used, then Section 4 discusses the basic results. Next, Section 5 examines whether the observed features are really caused by 3D effects or perhaps by some other factors. Finally, Section 6 offers a brief summary and discusses the results' main implications.

2. Observations

This study took advantage of the unprecedented abundance of high-quality, easy-to-use, and freely available cloud products from new Earth Observing System (EOS) satellites. In particular, it used observations by MODIS on board the Terra and Aqua satellites. The analysis focused on the operational 1 km-resolution cloud optical thickness product (Platnick et al. 2003), but it also considered the calibrated reflectances at 0.86 μm wavelength, the cloud phase product, and some sun-view and geolocation parameters. All products were generated by the Collection 4 version of the operational MODIS data processing software. The analysis used data from each Friday in November 2002: November 1, 8, 15, 22, and 29. The one-week separation between subsequent days reduced potential sampling biases, because it is unlikely that the same cloud systems could persist through several Fridays.

For each Friday we took 10 MODIS granules from the Terra and Aqua satellites, which yielded a total of 5 x (10 + 10) = 100 granules. (Each granule is an image covering an approximately 2000 km by 2000 km area.) The 10 granules were chosen so that they form a ring around the Earth at roughly 40° North latitude. Terra observed this ring in the morning, and Aqua, in the afternoon. The histogram of solar zenith angle is shown in Figure 1.

3. Methodology

Simple schematic arguments (Fig. 2) illustrate that 3D effects are expected to enhance cloud reflection into backscatter directions. Since 1D data processing algorithms do not account for this enhancement, they assume that clouds viewed from backscatter directions appear so bright because they are very thick. Therefore our basic approach to detecting 3D effects was to examine the question: Do 1D retrievals yield systematically larger optical thicknesses when clouds are viewed from backscatter directions? Obviously, the clouds' true optical thickness (τ) does not depend on the direction form which a satellite views them; therefore, a statistically significant increase in τ can indicate the presence of 3D effects. (Conceivably, factors other than 3D effects could also cause such increases in the observations, and so Section 5 will examine whether these other factors also play an important role.)

The geometry of MODIS observations implies that clouds are viewed from backscatter directions at one edge of MODIS images, and from forward scattering directions at the other edge (Figure 3). As a result, examining the view angle-dependence of retrieved τ values is equivalent to examining how τ varies across the satellite track. Let us note, however, that the Sun-synchronous orbits of the Terra and Aqua satellites imply that at 40° latitude, clouds are not viewed from the exact forward and backward directions, but approximately 50° off the plane of solar azimuth.

4. Results

Before examining the τ-retrieval results, let us briefly pause at the observed reflectances. Figure 4 reveals that their basic behavior is qualitatively consistent with 1D radiative transfer theory: Reflectances are lowest at nadir and increase in oblique directions, especially for forward scattering. However, there are also some qualitative differences that are consistent with 3D effects, which increase backscatter and reduce forward reflection. Most notably, the observed reflectances do not level off at very oblique view angles as 1D theory predicts (Fig. 4). Unfortunately, a quantitative comparison of observed and simulated reflectances would be a complicated task, because observational, environmental, and cloud parameters vary substantially across the observed scenes. Therefore we take advantage of the MODIS operational retrievals that already considered all these variations, and we turn our attention to the retrieved τ-values.

Figure 5 displays the view angle-dependence (i.e., cross-track variability) of the retrieved optical thicknesses' mean and standard deviation. The figure was obtained by combining all those pixels from the 100 MODIS granules that contained liquid phase clouds with $\tau > 2$. Pixels with $\tau < 2$ were excluded because the number of such pixels varies significantly with view direction due to a simple reason that has nothing to do with 3D radiative effects: The cloud masking algorithm (Ackerman et al. 1998; Platnick et al. 2003) is more effective in detecting thin clouds at oblique views, because the viewing path through the clouds is longer (than at overhead views).

The figure reveals significant increases at oblique backscatter directions, which is fully consistent with the expected influence of 3D radiative effects. We note that a similar figure for ice clouds (not shown) displays this trend even stronger—but because it would be difficult to separate the influence of 3D effects from the influence of uncertainties in ice crystal phase functions (Yang and Liou 1996), we limit the current study to liquid water clouds.

Figure 6 indicates that a major contribution to the increase in backscatter directions comes from an increase in the ratio of saturated pixels. Saturation occurs when the observed reflectances exceed the range in which 1D reflectances are sensitive enough to optical thickness for allowing meaningful retrievals. In such cases the retrievals do not return unrealistically high τ values, but instead report the maximum allowed τ value in the range of 98-100. The increase in the number of saturated pixels is easy to understand in terms of 3D effects: as 3D effects make clouds brighter in backscatter views, the saturation threshold will be exceeded more frequently. 3D effects increasing the rate of saturation not only increase the mean optical thickness but also alter the structure of cloud fields. This implies that one needs extra caution if oblique observations are included into studies of cloud structure using 2-point statistics such as structure functions, autocorrelation functions, power spectra, fractal dimensions or intermittency (e.g., Oreopoulos et al., 2000). Still, Figure 6b indicates that the increase in backscatter views is significant (up to 30% for $\Theta > 60°$) even if only non-saturated pixels (with $\tau < 98$) are considered.

While the increases in backscatter directions (especially for $\Theta > 50°$) can certainly come from 3D radiative effects, it is unclear whether the variations at less oblique views and in forward scattering views are related to 3D effects. As mentioned in the introduction, theoretical simulations and earlier observations showed that 3D effects tend to reduce reflection in forward directions, whereas Figures 5 and 6 show some increases with Θ. We are not yet ready to correctly interpret these increases; thus the present paper focuses only on interpreting the sharp increases observed in backscatter directions.

5. Influence of factors other than 3D radiative effects

In order to make sure that the τ-increases in backscatter directions are indeed caused by 3D radiative effects, this section examines a variety of factors that could conceivably also cause similar increases. Because the increase appears most pronounced in Figure 6a, this section uses the ratio of saturated pixels to explore possible alternative explanations for the τ-increase in backscatter directions.

Surface reflection: Figure 7 indicates that the τ-increase is present over both land and ocean surfaces. Since it is unlikely that the cloud retrievals would have such similar errors in the reflection characteristics of these very different surface types, one can exclude uncertainties in surface properties from the causes of τ-increase. (We note that the observations do not include either sun glints or direct back-reflection hotspots.)

Atmospheric correction: Errors in the retrieval algorithm's handling of gaseous absorption and Rayleigh scattering are not likely to contribute much to the τ-increase, since such errors would have similar effects for forward and back oblique views. Uncertainties in aerosol properties are also cannot be the main factor, because Figure 7 revealed that the τ–increase is strong over both land and ocean despite the typically very different aerosol properties over these surfaces.

Droplet scattering phase function: Uncertainties in the phase function are unlikely to cause the observed τ-increases, for three reasons. First, the ratio of saturated pixels (or the mean τ value) plotted as a function of the scattering angle (not shown) does not indicate any increase at scattering angles around 125°, which dominate at the regions of the τ-increase. Second, even though the Earth's curvature and orbital parameters result in similar scattering angles around $\Theta = 30°$ than around $\Theta = 60°$, the observations do not show any τ-increases around $\Theta = 30°$. Third, a comparison of the angular distribution of observed liquid and ice cloud reflectances revealed that if some ice clouds were mistakenly identified as liquid clouds, the mistake would act to reduce (and not enhance) the τ-increase.

Local time: Since the τ-increases are present in both the morning observations of Terra and in the afternoon observations of Aqua (Figure 8), it is unlikely that systematic cross-track changes in local time would play a major role in the observed τ-increases.

Latitude: Because of the orbital inclination of the Terra and Aqua satellites, MODIS observations have a systematic cross-track dependence: The areas observed at backscatter directions lie at slightly higher latitudes than the areas observed from overhead or forward scattering directions. To check whether this may cause the observed τ-increases, the importance of various latitudes (λ) across the MODIS track was equalized using the equation

$$R'_{\tau>98}(\Theta) = \frac{1}{N_\lambda} \sum_{\lambda_i=30^\circ}^{45^\circ} \frac{N_{\tau>98}(\lambda_i,\Theta)}{N_{\tau>2}(\lambda_i,\Theta)} \qquad (1)$$

where N_λ is the number of 1°-wide latitude bands in the 30°-45° range. (In this range, there are plenty observations at all view angles.) Figure 9 shows the τ-increase in backscatter directions even after equalizing the importance of various latitudes across the track, which means that the τ-increase does not arise because of a systematic latitude-dependence in cloud properties.

Solar zenith angle: Similarly to the latitude, the solar zenith angle (Θ_0) also varies systematically across MODIS images. However, the results (not shown) indicate that the τ-increase in backscatter directions remained strong even after equalizing the importance of various solar zenith angles similarly to Eq. (1). This indicates that the τ-increase is a manifestation of 3D radiative effects that depend on the viewing and not the solar zenith angle. This is different from the 3D effects described in some earlier studies (Loeb and Davies 1996; Loeb et al. 1997; Loeb and Coakley 1998).

Sampling noise: Some of the variations in Figures 5 and 6 are certainly caused by sampling noise—that is, by the random influence of individual cloud systems. However, it is very unlikely that the τ-increase in backscatter direction would be caused by sampling effects First of all, its magnitude is much larger than that of random variations at other view angles. Also , Figure 8 revealed that the τ-increase is present in both Terra and Aqua observations. This is important, because Terra and Aqua observed the same weather systems (with only a few hours difference), but the Terra and Aqua granules were not aligned. As a result, a weather system observed by Terra from oblique backscatter directions was usually observed by Aqua from different directions. This implies that if an individual cloud system caused the backscatter τ-increase in Terra observations, it would have caused a similar increase at different view angles in the Aqua observations.

6. Summary and conclusions

This study examined whether one can observe in real clouds a tendency that3D radiative interactions enhance cloud reflection into backscatter directions. In particular, it analyzed the view angle-dependence of cloud optical thickness values that were retrieved from MODIS observations. The idea was that if 3D effects do enhance back reflection, the 1D retrievals (not accounting for this effect) would yield larger optical thickness values when clouds are observed from back scatter, rather than overhead or forward scatter view directions.

The paper used the 1 km-resolution MODIS cloud optical thickness product. The statistical analysis of 100 approximately (2000 km)^2 mid-latitude images from November 2002 revealed that indeed, 1D retrievals yield systematically higher optical depths when clouds are viewed from back scattering directions. Both the mean and the standard deviation of cloud optical depth distributions increased by up to 30%, and the number of pixels too bright for accurate retrievals jumped by up to a factor of 5 for oblique backscatter views.

The results have some important implications for satellite remote sensing:

- When the sun is less than 30°-40° above the horizon, one should exercise great caution in using 1D cloud property retrievals based on oblique backscatter observations. In some studies it may be prudent to limit the use of 1D retrievals to viewing zenith angles less than 50°. This implication can be especially important for geostationary satellites, which always observe some areas at such oblique angles. For backward viewing angles larger than 50°, one can expect a substantial overestimate in 1D cloud optical depth retrievals. The overestimate grows sharply with viewing zenith angle.
- Because 3D radiative effects greatly modify the structure of the retrieved cloud optical depth fields (e.g., they increase the number of very thick pixels), one should be very careful about including such observations into studies of horizontal variability, such as intermittency or fractal properties.

References

Ackerman, S. A., K. I. Strabala, W. P. Menzel, R. A. Frey, C. C. Moeller, and L. E. Grumley, 1998: Discriminating clear sky form clouds with MODIS. *J. Geophys. Res.*, **103**, 32,141-32,158.

Buriez, J.-C., M. Doutriaux-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.

Davies, R., 1984: Reflected solar radiances from broken cloud scenes and the interpretation of scanner measurements. *J. Geophys. Res.*, **89**, 1259-1266.

Davis, A., A. Marshak, R. F. Cahalan, and W. J. Wiscombe, 1997: The Landsat scale break in stratocumulus as a three-dimensional radiative transfer effect, Implications for cloud remote sensing. *J Atmos. Sci.*, **54**, 241-260.

Fauré, T., H. Isaka, and B. Guillemet, 2001: Neural network retrieval of cloud parameters of inhomogeneous and fractional clouds. Feasibility study. *Remote Sens. Environ.*, **77**, 123-138.

Kobayashi, T., 1993: Effects due to cloud geometry on biases in the albedo derived from radiance measurements. *J. Climate*, **6**, 120-128.

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.

Loeb, N. G., and R. Davies, 1997: Angular dependence of observed reflectances: A comparison with plane-parallel theory. *J. Geophys. Res.*, **102**, 6865-6881.

Loeb, N. G., and J. A. Coakley, 1998: Inference of marine stratus cloud optical depths from satellite measurements: Does 1D theory apply? *J. Climate*, **11**, 215-233.

Loeb, N. G., T. Várnai, and R. Davies, 1997: Effect of cloud inhomogeneities on the solar zenith angle dependence of nadir reflectance. *J. Geophys. Res.*, **102**, 9387-9395.

Marshak, A., A, Davis, R. F. Cahalan, and W. Wiscombe, 1998: Nonlocal independent pixel approximation: Direct and inverse problems. *IEEE Trans. Geosci.*, **36**, 192-205.

Oreopoulos, L., R. F. Cahalan, A. Marshak, and G. Wen, 2000: A new normalized difference cloud retrieval technique applied to Landsat radiances over the Oklahoma ARM site. *J. Appl. Meteor.*, **39**, 2305-2321.

Oreopoulos, L., A. Marshak, R. F. Cahalan, and G. Wen, 2000: Cloud 3D effects evidenced in Landsat spatial power spectra and autocorrelation functions. *J. Geophys. Res.*, **105**, 14777-14788.

Platnick, S., M. D. King, S. A. Ackerman, W. P. Menzel, B. A. Baum, J. C. Riédi, and R. A. Frey, 2002: The MODIS cloud products: Algorithms and examples from Terra. *IEEE Trans. Geosci. Remote Sens.*, **41**, 459-473.

Rossow, W., 1989: Measuring cloud properties from space: A review. *J. Climate*, **2**, 201-213.

Stamnes, K., S.-C. Tsay, W. J. Wiscombe and K. Jayaweera, 1988: Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. *Appl. Opt.*, **27**, 2502–2512.

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

Yang, P., and K. N. Liou, 1996: Finite-difference time domain method for light scattering by small ice crystals in three-dimensional space, *J. Opt. Soc. Am.*, **10**, 2072-2085.

Zuidema, P., R. Davies, and C. Moroney, 2003: On the angular radiance closure of tropical cumulus congestus clouds observed by MISR. *J. Geophys. Res.*, in press.

Figure captions

Figure 1. Histogram of the used observations' solar zenith angle.

Figure 2. 3D effects that enhance cloud reflection into backscatter directions. The solid arrow indicates the paths radiation follows in a 3D scene, while dashed lines indicate the path radiation would follow in a 1D world. (a) Trapping of radiation in 3D clouds. This mechanism redirects photons that—because of the droplet phase function's forward scattering peak—would create intense forward reflection in 1D clouds. (b) Escape of backscatter radiation. This mechanism enhances back reflection from sunlit slopes.

Figure 3. A schematic view of MODIS observation geometry.

Figure 4. A qualitative comparison of the view angle-dependence the observed 0.86 μm reflectances to 1D simulation results. In order to minimize the effects of underlying surface, only the brighter 50% of observed cloudy pixels are included at each view angle. The 1D results come from DISORT (Stamnes et al., 1988) calculations for conditions similar to the observations. The simulation curve is plotted above the observational one only for schematic comparisons.

Figure 5. View angle-dependence of the mean and standard deviation of τ-values in the operational MODIS cloud product. These statistics were calculated using all liquid clouds with $\tau > 2$ in 100 MODIS granules. Over 60,000 cloudy pixels were used in each (approximately 0.1°-wide) view angle bin corresponding to a single column in MODIS images.

Figure 6. (a) Ratio of pixels with $\tau > 98$. The ratio (R) is calculated as $R(\Theta) = \frac{N_{\tau>98}(\Theta)}{N_{\tau>2}(\Theta)}$, where N is the number of pixels and Θ is the viewing zenith angle. (b) Mean optical thickness of pixels with $2 < \tau < 98$.

Figure 7. Ratio of saturated pixels ($\tau > 98$) over land and ocean. The ratio is calculated the same way as in Figure 4a.

Figure 8. Ratio of saturated pixels ($\tau > 98$) in MODIS observations from the Terra and Aqua satellites. The ratio is calculated the same way as in Figure 4a.

Figure 9. Ratio of saturated pixels ($\tau > 98$) after the influence of various latitudes across the MODIS track is equalized using Eq. (1).

Figures

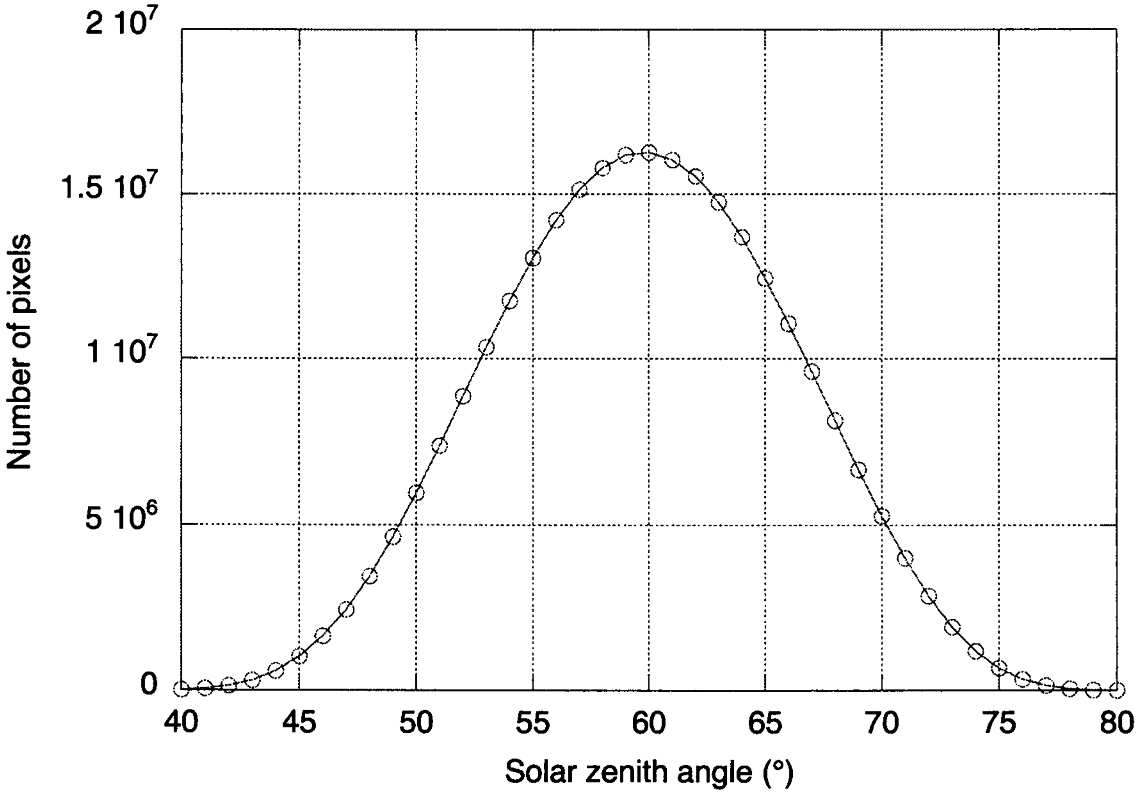

Figure 1.

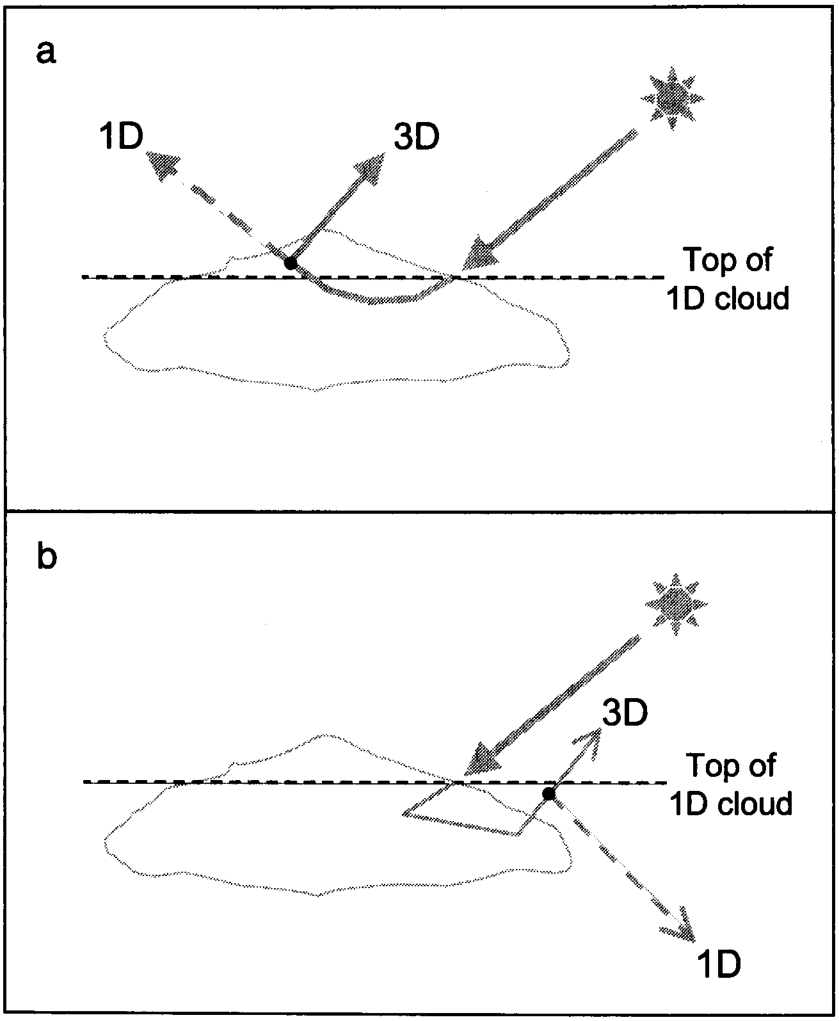

Figure 2.

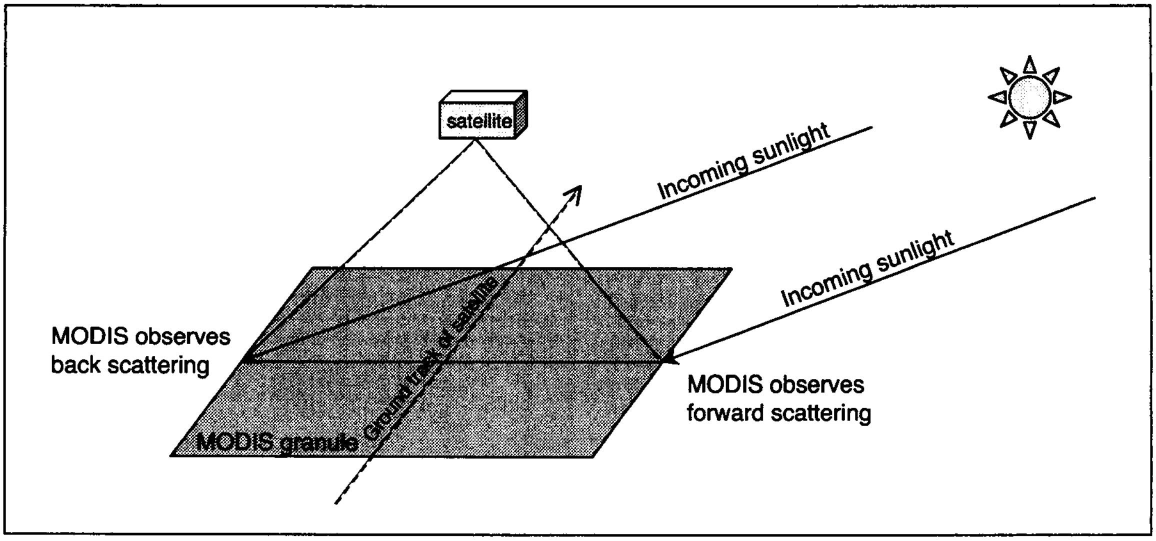
satellite
Incoming sunlight
Incoming sunlight
MODIS observes back scattering
MODIS observes forward scattering
Ground track of satellite
MODIS granule

Figure 3.

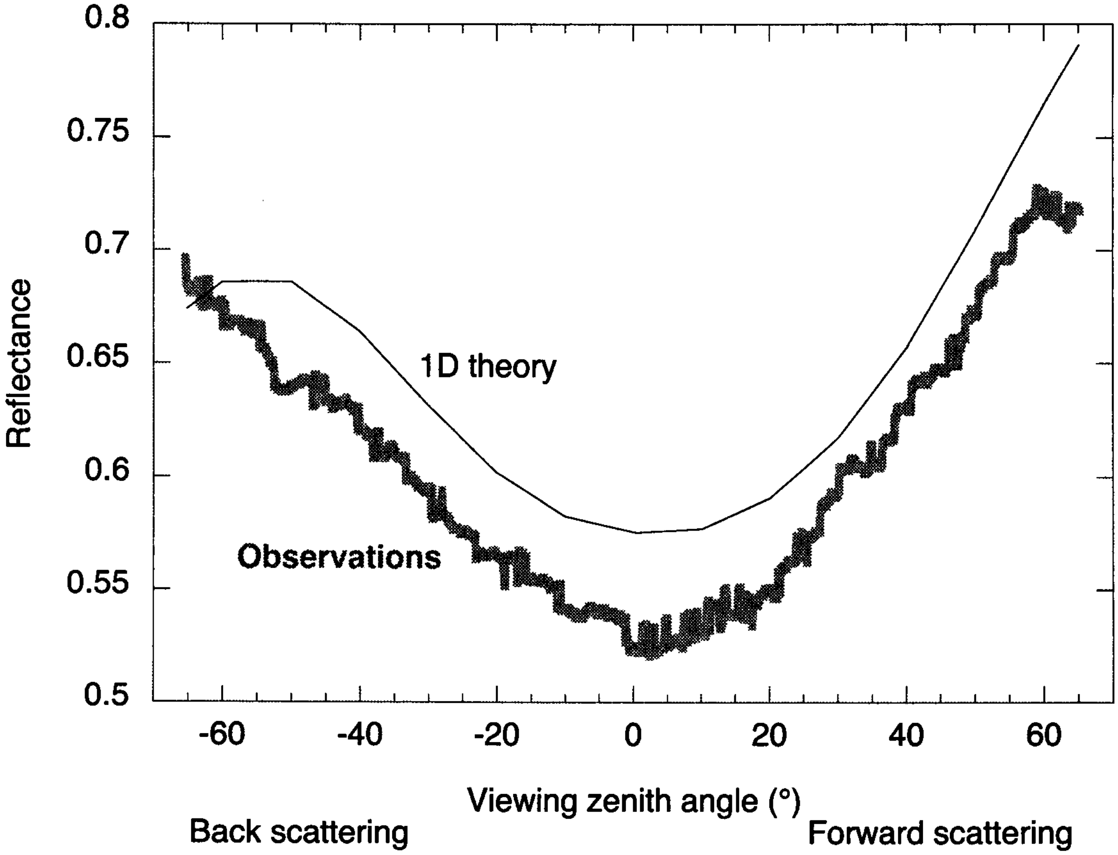
0.8
0.75
0.7
0.65
0.6
0.55
0.5
Reflectance
1D theory
Observations
-60
-40
-20
0
20
40
60
Viewing zenith angle (°)
Back scattering
Forward scattering

Figure 4

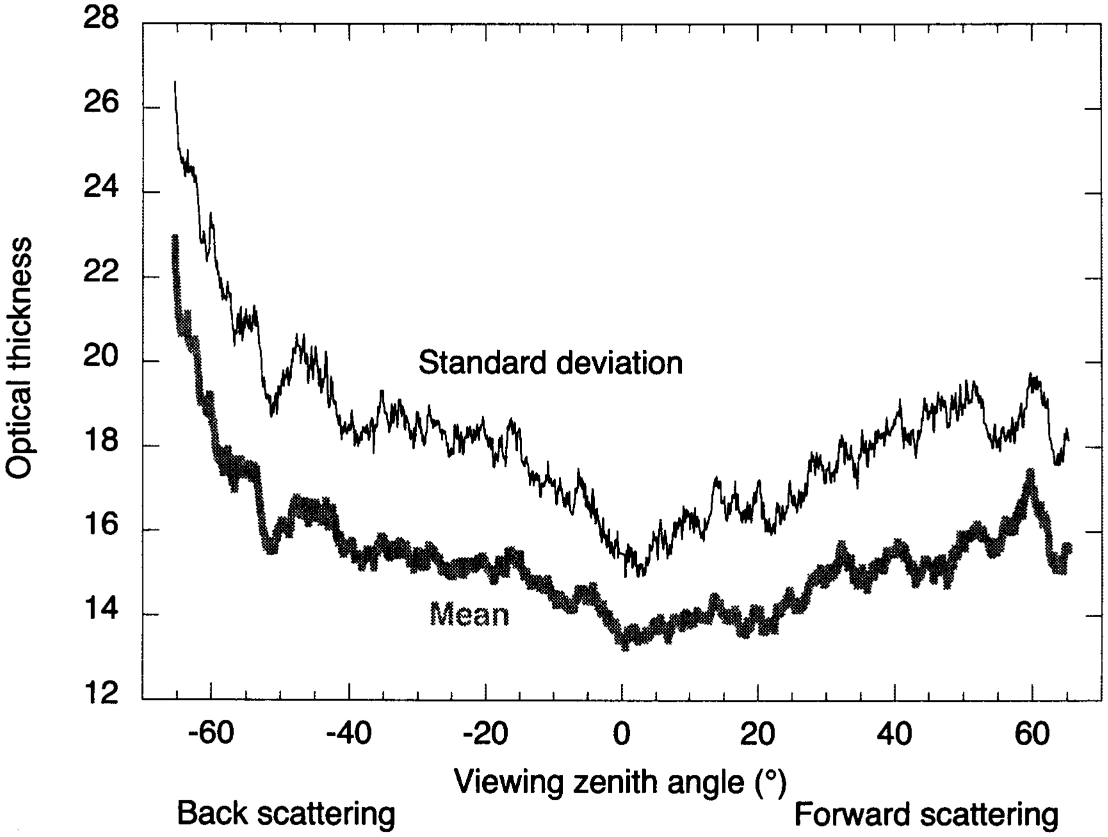
28
26
24
22
20
18
16
14
12
Optical thickness
-60
-40
-20
0
20
40
60
Viewing zenith angle (°)
Back scattering
Forward scattering
Standard deviation
Mean

Figure 5.

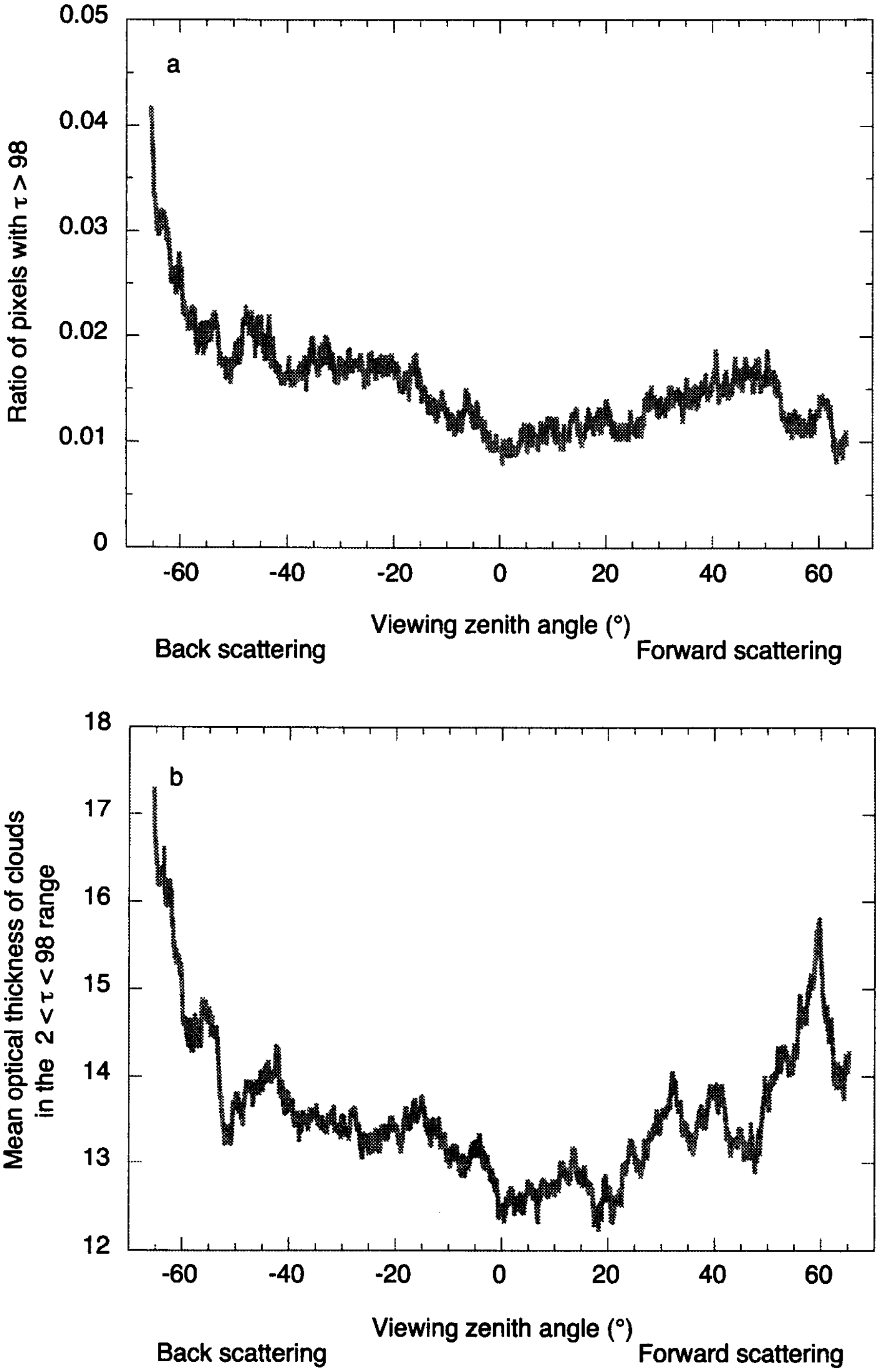
a
Ratio of pixels with τ > 98
0.05
0.04
0.03
0.02
0.01
0
-60
-40
-20
0
20
40
60
Viewing zenith angle (°)
Back scattering
Forward scattering
b
Mean optical thickness of clouds in the 2 < τ < 98 range
18
17
16
15
14
13
12
-60
-40
-20
0
20
40
60
Viewing zenith angle (°)
Back scattering
Forward scattering

Figure 6.

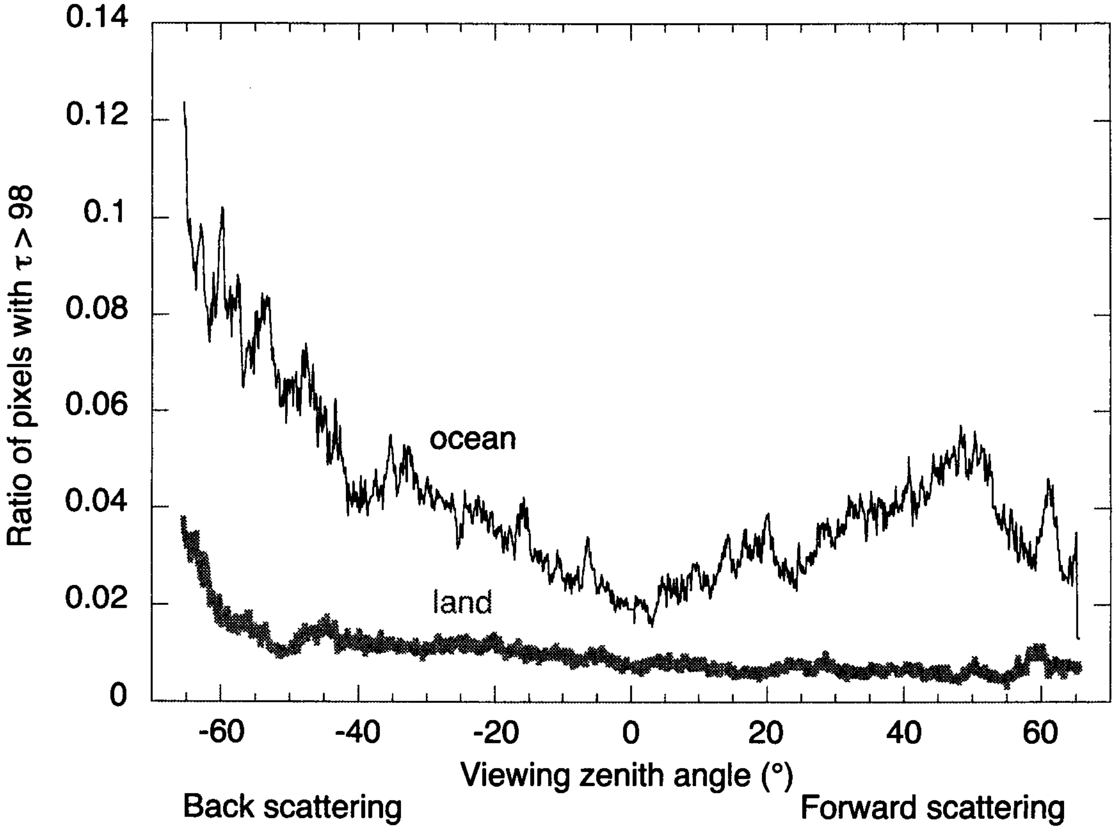
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ratio of pixels with τ > 98
ocean
land
-60
-40
-20
0
20
40
60
Viewing zenith angle (°)
Back scattering
Forward scattering

Figure 7.