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View angle dependence of cloud optical thicknesses retrieved by Moderate Resolution Imaging Spectroradiometer (MODIS)

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[1] This study examines whether cloud inhomogeneity influences the view angle dependence of MODIS cloud optical thickness retrieval results. The degree of cloud inhomogeneity is characterized through the local gradient in 11 μm brightness temperature. The analysis of liquid phase clouds in a 1 year long global data set of Collection 4 MODIS data reveals that while optical thickness retrievals give remarkably consistent results for all view directions if clouds are homogeneous, they give much higher τ-values for oblique views than for overhead views if clouds are inhomogeneous and the Sun is fairly oblique. The mean optical thickness retrieved for the most inhomogeneous third of cloudy pixels is more than 40% higher for oblique views than for overhead views if the solar zenith angle exceeds 60°. After considering a variety of possible scenarios, the paper concludes that the most likely reason for the increase lies in three-dimensional radiative interactions that are not considered in current, one-dimensional retrieval algorithms. Namely, the radiative effect of cloud sides viewed at oblique angles seems to contribute most to the enhanced optical thickness values. The results presented here will help understand and estimate cloud retrieval uncertainties related to cloud inhomogeneity and may eventually help correct for the observed view angle-dependent biases.

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1. Introduction

[2] Satellite remote sensing is such a complex task that until now it could be done only by using one-dimensional (1-D) radiative transfer theory, which assumes that cloudy pixels are fully covered by horizontally homogeneous clouds and that the pixels' radiative properties are not affected by cloud variability in nearby areas. The use of 1-D theory is often referred to as the plane-parallel approximation. It is true that some recently proposed methods [e.g., *Marshak et al.*, 1998a; *Oreopoulos et al.*, 2000a; *Faure et al.*, 2001; *Várnai and Marshak*, 2002a; *Iwabuchi and Hayasaka*, 2003; *Cornet et al.*, 2004, 2005] use some aspects of three-dimensional (3-D) radiative transfer theory for retrievals of cloud optical thickness, but these novel methods are not yet ready for operational use.

[3] In recent years, several observational studies examined whether 1-D radiative theory gives accurate results in satellite remote sensing. These studies found that, under certain conditions, 3-D effects cause significant problems. Specifically, they revealed that 3-D effects can make clouds appear too smooth or too rough [e.g., *Marshak et al.*, 1995; *Davis et al.*, 1997; *Oreopoulos et al.*, 2000b], too bright and thick [e.g., *Loeb and Davies*, 1996; *Loeb and Coakley*, 1998], and artificially asymmetric [*Várnai and Marshak*, 2002a, 2002b].

[4] While the papers above focused mainly on overhead satellite views, some studies examined 3-D 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 3-D effects [*Rossow*, 1989]. Using multiangle MISR (Multiangle Imaging SpectroRadiometer) observations, however, *Horváth and Davies* [2004] showed that the angular pattern of cloud reflection rarely fits the expectations based on the plane-parallel approximation. 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 [*Loeb and Davies*, 1997; *Loeb and Coakley*, 1998; *Buriez et al.*, 2001] found that for low Sun, 3-D interactions such as shadowing make clouds appear too dark from oblique views facing the Sun, and that this makes 1-D retrievals underestimate cloud optical thickness. Theoretical studies [e.g., *Davies*, 1984; *Kobayashi*, 1993; *Loeb et al.*, 1998; *Szczap et al.*, 2000; *Várnai*, 2000; *Chambers et al.*, 2001; *Iwabuchi and Hayasaka*, 2002] have long suggested that 3-D 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 back-

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scatter from sunlit slopes. *Zuidema et al.* [2003] found that in highly inhomogeneous cumulus congestus clouds, oblique backscatter reflectances observed by MISR exceeded 3-D radiative transfer calculations based on cloud structure retrieved from the MISR nadir camera using the plane-parallel approximation. Recently, *Marchand and Ackerman* [2004] found that stratocumulus reflection in backscatter direction was stronger in MISR observations than in 1-D or even 2-D simulations for cloud structures derived from a variety of ground-based and satellite observations.

[5] Finally, theoretical studies [e.g., *Davies*, 1984; *Bréon*, 1992; *Kobayashi*, 1993] also indicated that cloud inhomogeneities can enhance reflection through cloud sides into oblique side scatter directions relative to cloud reflection into overhead direction. The observations of *Minnis* [1989] revealed that cloud side viewing must occur frequently, because it increases cloud coverage significantly for oblique views, but the implications of this effect on optical thickness retrievals have not yet been determined through observations.

[6] The goal of this paper is to analyze the view angle dependence of a one yearlong MODIS cloud optical thickness data set, and to examine whether cloud inhomogeneity has a significant influence on this view angle dependence. Section 2 describes the data we analyzed, section 3 outlines our methodology, and section 4 presents the results of our analysis. Section 5 then discusses potential reasons for the observed view angle dependence, including the effects of cloud sides on the retrievals. Finally, section 6 offers a brief summary and discusses the results' main implications.

2. Observations

[7] 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 a data set extracted from the continuous stream of incoming MODIS observations at the Goddard Earth Sciences Data and Information Services Center (GES DISC) MODIS data pool. The data set includes observations from virtually all daytime granules from the MODIS instruments on both the Terra and Aqua satellites for a one yearlong period ranging from September 2004 to August 2005. The data set includes 1-km-resolution Collection 4 MODIS products such as the 11 μm brightness temperature, cloud phase, cloud optical thickness, and cloud top pressure, as well as geolocation parameters such as latitude, longitude, surface type, and Sun-view geometry. We note that while most cloud parameters are retrieved at 1 km resolution using 1-km-resolution radiance measurements, cloud top pressure is retrieved at 5 km horizontal resolution. The retrievals include both overcast and partially cloudy pixels. To reduce data volume, these parameters were saved only for about every 14th row in the MODIS images. To help examine the influence of local cloud variability, 11 μm brightness temperature and cloud optical thickness values were also saved for both neighbors of each row. Finally, we note that in order to avoid the effects of uncertainties in cloud detection and in ice crystal scattering phase functions, this study analyzed only liquid phase pixels that were flagged as "high confidence" by the operational MODIS optical thickness retrieval algorithm.

3. Methodology

[8] MODIS is suitable for analyzing the view angle dependence of retrieved cloud parameters because clouds are viewed from overhead direction at the MODIS swath center and from highly oblique directions at the swath edges, with maximum viewing zenith angles exceeding 60°. It is important to note that the oblique views are not aligned with the solar azimuth and represent side scattering at both swath edges: At low solar elevations, observations are typically from 65° and 110° relative azimuths at the two swath edges (Figure 1). While the range of relative azimuths is quite narrow for low Sun (e.g., 65° ± 10° for 60° solar zenith angle), this range moves a little closer to the solar plane and is wider for high Sun (e.g., 55° ± 15° for 30° solar zenith angle).

[9] One approach to identifying the influence of 3-D effects is to contrast the view angle dependence of optical thicknesses (τ) retrieved for more homogeneous and more inhomogeneous clouds, for which 3-D effects are expected to be weaker and stronger, respectively. Following *Várnai and Marshak* [2002a], we characterize the degree of inhomogeneity at a given pixel through ΔT, the 11 μm brightness temperature gradient in a direction close to the solar azimuth:

$$\Delta T = \frac{|T_f - T_b|}{d} \tag{1}$$

where T is brightness temperature, the subscripts f and b identify the neighboring pixels in front and behind our pixel, as viewed from the solar direction, and d is the distance between these two neighboring pixels ($d = 2$ km or, if the solar azimuth is close to diagonal in the MODIS image, $d = \sqrt{2} \cdot 2$ km). We note that using the range of brightness temperatures in a 3 × 3 pixel window for characterizing cloud variability produced nearly identical results to our approach. In contrast, using τ-variability proved less effective in separating homogeneous and inhomogeneous clouds for the purpose of creating two cloud categories with distinct view angle dependencies. This is because cloud top variability (implying brightness temperature variations) causes stronger radiative effects than optical thickness variability caused by internal variations [e.g., *Loeb et al.*, 1997, 1998; *Marshak et al.*, 1998b; *Várnai and Davies*, 1999; *Iwabuchi and Hayasaka*, 2002].

[10] Using the ΔT values defined in equation (1), we separated cloudy pixels that had high-confidence liquid phase τ-retrievals into three equally populous categories based on the degree of local cloud variability. The thresholds separating the three categories were determined dynamically in our tests, ensuring that even if the ΔT values vary across the satellite track, one third of cloudy pixels is assigned to each category for all view angles. The overall thresholds tend to be around 0.3°–0.5°C/km for the most homogeneous category and 1.1°–1.5°C/km for the most heterogeneous category. Assuming a 6 K/km vertical temperature gradient, these values correspond to roughly

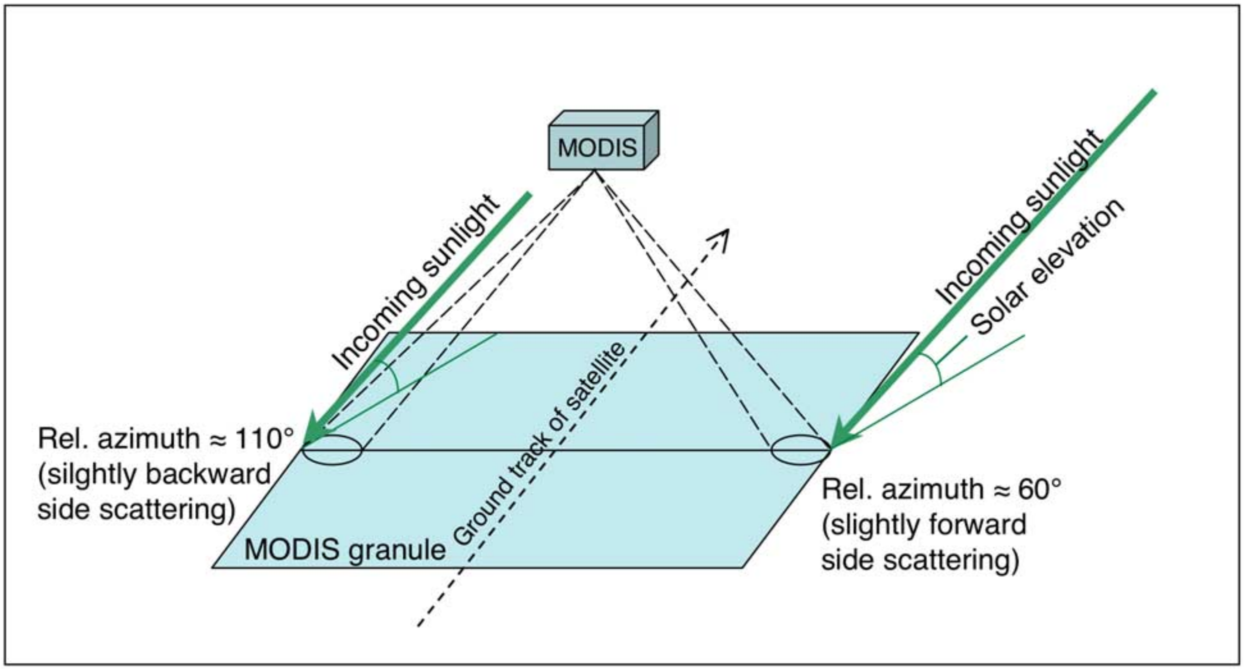

Figure 1. Schematic view of MODIS observational geometry.

50–80 m and 180–250 m altitude changes over 1 km horizontal distance for the homogeneous and inhomogeneous thresholds, respectively. We note that if constant thresholds are used to separate the three cloud categories, the exact results are slightly different from the results presented below, but their qualitative behavior is similar.

4. Results

[11] Considering a variety of solar zenith angles (θ_0), Figure 2 shows the way the mean retrieved τ-values change with view angle (θ) for the most homogeneous and most inhomogeneous third of cloudy pixels. Figure 2 clearly shows that homogeneous clouds tend to be thicker than inhomogeneous clouds. It also confirms the findings of *Loeb and Davies* [1996] and *Loeb and Coakley* [1998], that retrieved τ-values increase with solar zenith angle. While we do not examine the reasons for this increase in the current paper, we note that the earlier studies, along with *Loeb et al.* [1997], attributed the increase to 3-D radiative effects. We also note that although the overhead view optical thicknesses increase by similar amounts for homogeneous and inhomogeneous pixels as the solar zenith angle changes from 30° to 75°, this does not imply that cloud variability does not affect (and hence cannot cause) the increase: Because of the nonlinearity of 1-D reflectance versus τ curves, the similar increase in optical thickness arises from a much larger increase in reflectance for the thinner inhomogeneous clouds than for the thicker homogeneous clouds.

[12] Figure 2a indicates that for homogeneous clouds, the plane-parallel approximation produces consistent results that, except for a hump appearing for very oblique Sun, do not change much with view direction. Figure 2b, however, reveals that for inhomogeneous clouds, the plane-parallel approximation yields substantially higher τ-values for oblique views than for overhead views if the Sun is fairly oblique, with differences exceeding 50% for the most oblique solar zenith angles.

[13] For inhomogeneous clouds the U-shaped behavior of retrieved cloud optical thicknesses with respect to viewing angle θ can be approximated well by second-order polynomials with θ_0-dependent coefficients,

$$\tau(\theta;\theta_0) = a(\theta_0) + b(\theta_0)\cdot\theta + c(\theta_0)\cdot\theta^2. \quad (2)$$

In this equation, coefficient c characterizes the depth of the U shape.

[14] Figures 3 and 4 show that the U shape for inhomogeneous clouds tends to be deeper over land than over ocean. This is consistent with the fact that the observed ΔT local temperature gradients tend to be larger over land than over ocean, perhaps because stronger surface heating causes stronger convection and hence bumpier clouds over land. We note, however, that while small-scale variability is larger over land, *Oreopoulos and Cahalan* [2005] found that large-scale variability over 1° by 1° areas tends to be stronger over ocean. Finally, we also note that Figure 3 is in agreement with earlier studies [e.g., *Hahn et al.*, 2001] which showed that clouds tend to be thicker over land than over ocean.

[15] Figure 5 indicates that the U shape is stronger for high water clouds, which tend to have larger variability than low clouds. This is consistent with high clouds being thicker both optically and geometrically, which allows more pronounced inhomogeneities. Naturally, the distribution of high and low clouds is influenced by regional effects, for example some oceanic areas are dominated by low-level stratus clouds. Figure 6 shows that for the most inhomoge-

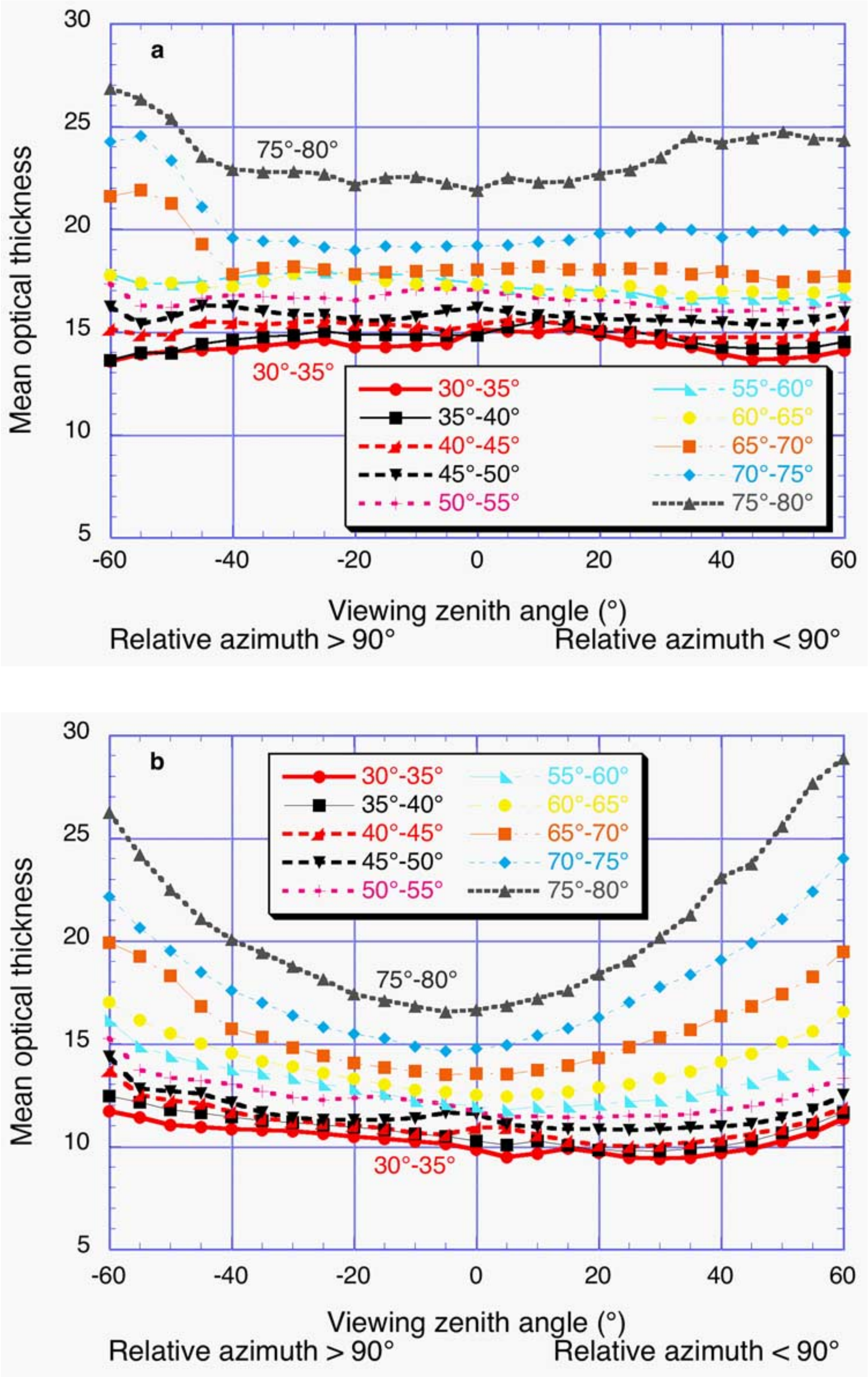

Figure 2. View angle dependence of mean retrieved optical thickness. Only liquid phase clouds with high-confidence retrievals are considered. Each line represents a separate solar zenith angle (θ_0) interval. (a) Most homogeneous third of cloudy pixels. (b) Most inhomogeneous third of cloudy pixels.

neous third of cloudy pixels, the difference between optical thicknesses retrieved at overhead and oblique views is significant throughout the entire range of cloud thicknesses: For oblique observations, optical thicknesses smaller and larger than 11 are less and more frequent, respectively. Finally, the results (not shown) indicate that the U shape is similar over the Northern and Southern hemispheres, for the Terra and Aqua satellites, and for various seasons

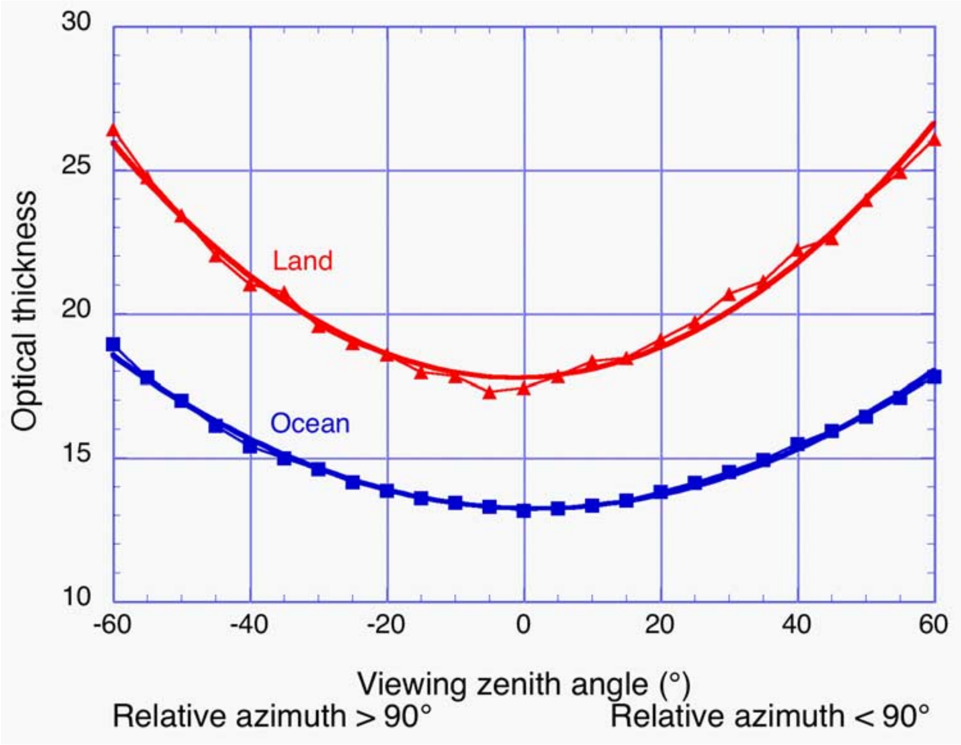

Figure 3. View angle dependence of mean optical thickness of inhomogeneous clouds over land and ocean. For increased clarity, each curve represents the average for 5 different solar zenith angle intervals ranging from 55 to 80°. The thick solid lines represent second-order polynomial fits to the curves.

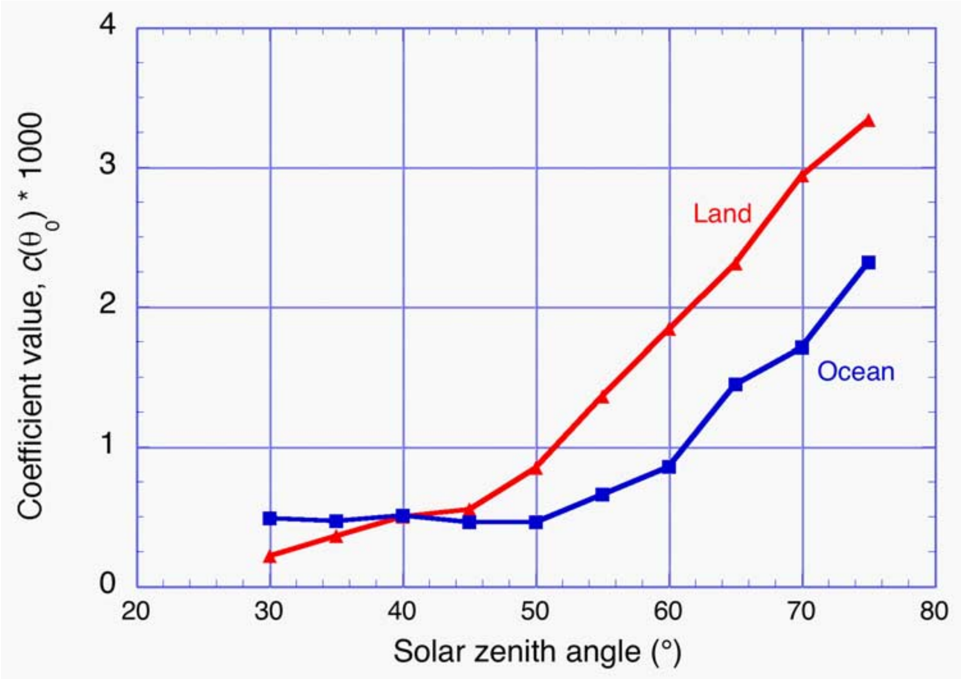

Figure 4. Solar zenith angle dependence of $c(\theta_0)$ quadratic coefficient values that were obtained by fitting second-order polynomials to the view angle dependence of τ-values retrieved for inhomogeneous pixels. The coefficient is an indicator of how pronounced the U-shaped view angle dependence of retrieved mean τ is.

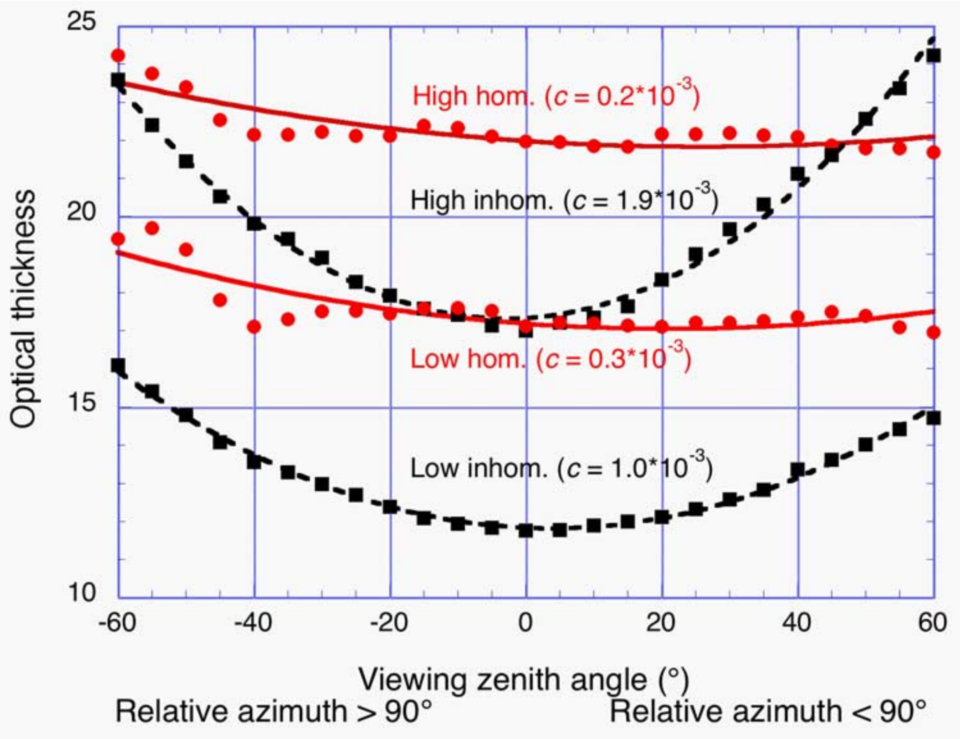

Figure 5. View angle dependence of mean τ for the most homogeneous and most inhomogeneous third of cloudy pixels that have MODIS-estimated cloud top pressures below and above 700 hPa. Accordingly, the "high" and "low" curves represent clouds with tops higher and lower than about 3 km, respectively. For increased clarity, each curve represents the average for five different solar zenith angle intervals ranging from 55° to 80°. The figure also displays the c coefficients obtained by fitting a second-order polynomial to each curve.

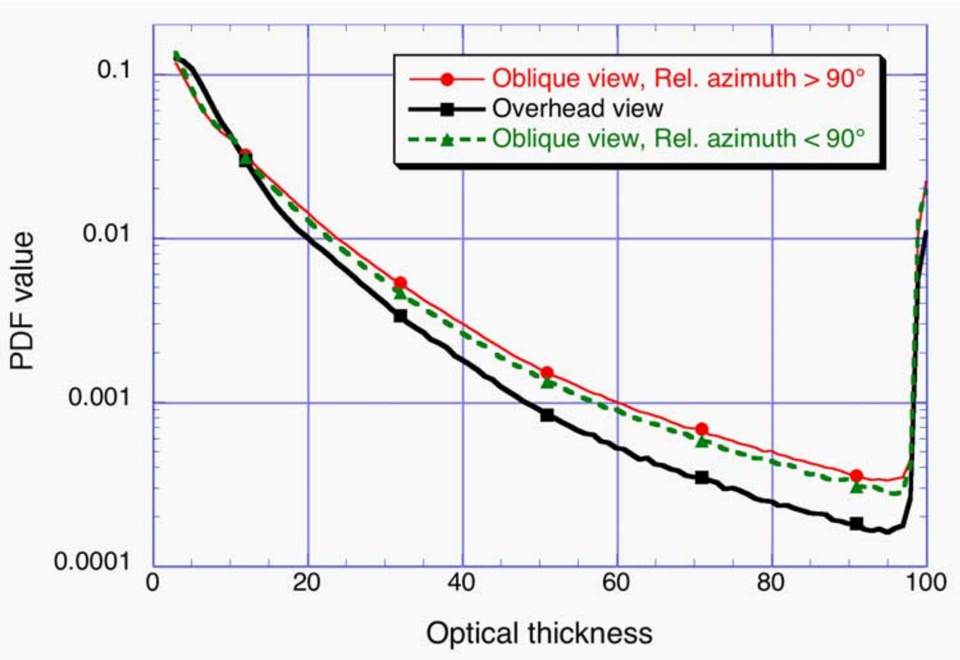

Figure 6. Probability distribution function (PDF) of τ for the most inhomogeneous third of cloudy pixels for overhead view and for oblique views slightly oriented toward forward and backscatter. The viewing zenith angle is in the 50–60° and the 0–5° range, respectively; the solar zenith angle is between 60 and 70°.

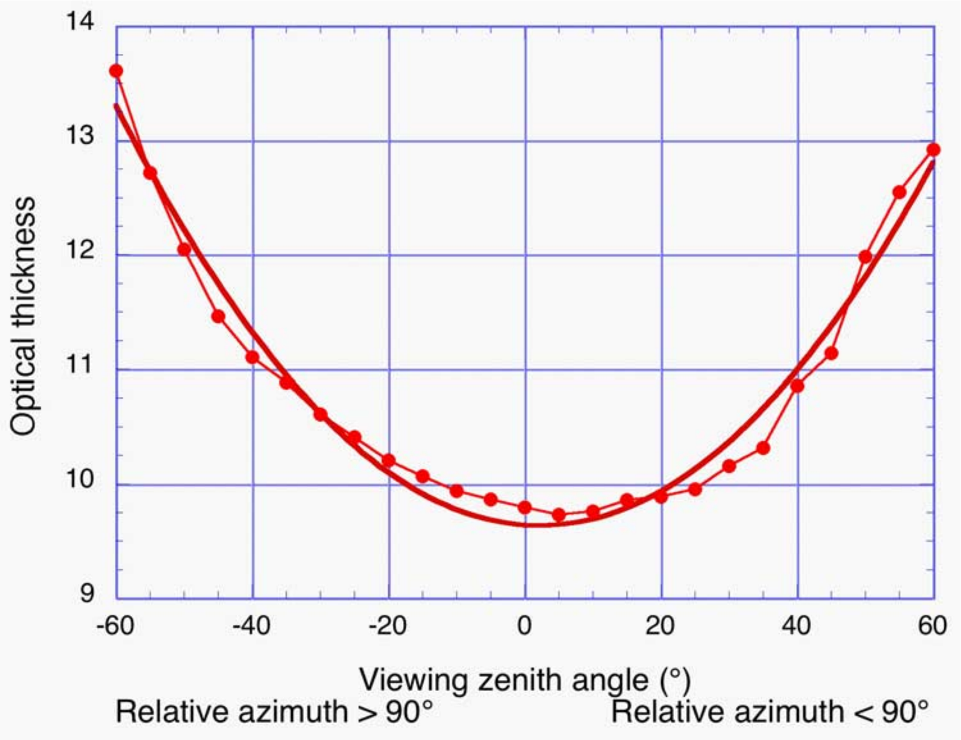

Figure 7. View angle dependence of mean τ for inhomogeneous pixels with 11 μm brightness temperatures warmer than 0°C, for solar zenith angles ranging from 55 to 80°. The thick line represents a second-order polynomial fit to the data using equation (2), with $c = 0.95*10^{-3}$.

throughout the year. This allows us to conclude that the presence of the U shape is not restricted to a particular cloud type or location, but is a general feature of MODIS retrievals for inhomogeneous clouds.

5. Potential Reasons for the Observed Behaviors

[16] This section examines whether the U shape in Figure 3 may arise from (1) the true behavior of inhomogeneous clouds, (2) inhomogeneous and homogeneous clouds occurring at different altitudes and over different surfaces, (3) uncertainties in cloud phase or cloud altitude, (4) cross-track changes in MODIS pixel size, and (5) the viewing of cloud sides from oblique directions.

[17] We first examine whether the U shape may reflect the true behavior of inhomogeneous clouds. This could occur, for example, if the Sun-synchronous orbits of the Terra and Aqua satellites resulted in the local time of observations to coincide with a minimum in the daily cycle of cloud development at the swath center. However, it appears unlikely that cross-track variations in local time or latitude, combined with the latitudinal distribution of cloud properties and the daily cycle of cloud development, could cause the U shapes observed for inhomogeneous clouds, because the curves remain similar for various combinations of satellite, hemisphere, and season, even though the local times and latitudes of observations are quite different for the various combinations. Thus it is more likely that the U shapes do not reflect the true behavior of inhomogeneous clouds, but are caused by some artifact in the remote sensing retrievals instead. Still, it is possible that systematic cross-track variations in latitude and local time cause some steady cross-track trends that may influence the relative magnitude of increases at the two swath edges.

[18] The next question to consider is whether the difference between the behaviors of homogeneous and inhomogeneous clouds is caused by inhomogeneity itself or by some other difference between the populations of homogeneous and inhomogeneous clouds. Figures 3 and 5 imply that the U shapes do not arise from inhomogeneous clouds occurring over different surfaces or at different altitudes than homogeneous clouds. Another possibility is that if, because of different updraft speeds, ice crystals had different shapes in homogeneous and inhomogeneous clouds, or if cloud inhomogeneity made it more difficult to detect cloud phase accurately, ice contamination in our supposedly liquid cloud data set could cause different view angle dependencies for homogeneous and inhomogeneous clouds. However, this is also unlikely since, as shown in Figure 7, the U shape is present even if only warm pixels with brightness temperatures exceeding 0°C are considered.

[19] As a result of the considerations above, it appears very likely that the U shapes in Figure 3 are indeed caused by cloud inhomogeneity. In this case the coefficient c of the second-order polynomial that best fits the U shape characterizes not only the depth of the U shape, but also the radiative effects of cloud inhomogeneity.

[20] One potential mechanism for the U-shaped behavior would be if cloud variability over the operational cloud top pressure retrievals' 5 km by 5 km domain introduced biases into the retrieved pressure values, and this caused errors in atmospheric correction over inhomogeneous clouds.

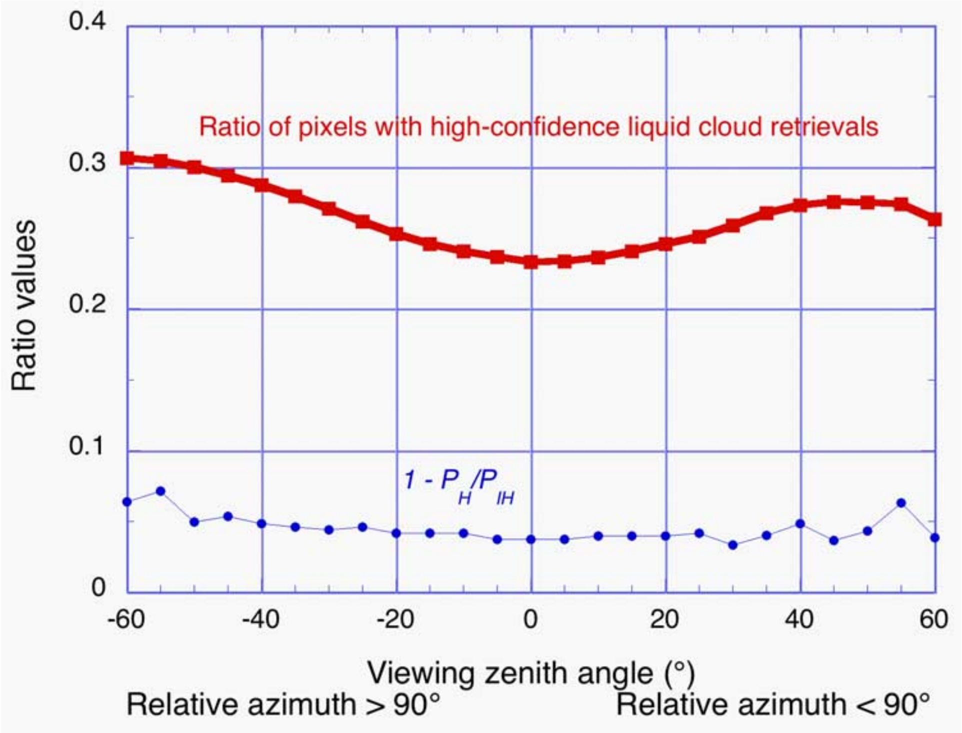

Figure 8. View angle dependence of cloud retrieval statistics for solar zenith angles ranging from 55 to 80°. The thick line indicates the ratio of pixels with high-confidence liquid phase cloud retrievals. (The typical number of pixels in each view angle bin is around 20 million.) The thin line shows 1.0 minus the ratio of 5th highest percentile cloud top pressure values in the homogeneous and inhomogeneous categories, $1 - P_{\mathrm{H}}/P_{\mathrm{IH}}$.

Because absorption by tropospheric gases is negligible at visible MODIS wavelengths, the effects would be strongest in the correction for Rayleigh scattering. However, simple 1-D calculations indicate that errors in cloud altitude could cause much weaker effects than those observed, and that if an error in altitude increased the retrieved τ-values at one edge of the swath, the same altitude error would decrease the τ-values at the other edge, which is inconsistent with the observations showing similar increases at both edges of the swath.

[21] Another consideration is that pixels near the swath edges cover more than 4 times larger areas than those at the center, as the larger view angles and Earth-satellite distances increase pixel dimensions more than two-fold. Increases in MODIS pixel size for oblique views can influence the view angle dependence of retrieved optical thicknesses because averaging radiances over larger areas cause stronger plane-parallel biases [e.g., *Oreopoulos and Davies*, 1998]. Because of the concavity of the 1-D reflectance versus τ curve, however, averaging always decreases the retrieved τ-values, and so stronger averaging at oblique views would create a ∩ shape rather than the U shape observed in Figure 3.

[22] Increases in pixel size could also cause the observed U shapes by preventing the detection of some thin clouds at the swath edges, thus yielding a smaller but thicker set of cloudy pixels. However, Figure 8 shows that this is not the case, as the ratio of cloudy pixels does not drop for oblique views. Moreover, Figure 8 also shows that the cross-track behavior of the highest retrieved cloud top pressure values is similar for homogeneous and inhomogeneous clouds. This implies that the retrievals do not miss more of the usually thin low-level clouds in the inhomogeneous than in the homogeneous category, which is another indication that the observed U shapes are not caused by cloud detection issues.

[23] Considering the more pronounced nonlinearity of 1-D τ versus reflectance curves for oblique views, 3-D effects could conceivably create the observed U shapes by increasing only the variability of reflectance fields, without changing their mean values. In this case, however, the U shape would be limited to pixels brightened by 3-D effects, whereas in the observations the U shape appears even for pixels for which $T_{\mathrm{f}} < T_{\mathrm{b}}$, which tend to lie on slopes facing away from the Sun and to be darkened by 3-D effects (Figure 9). We note that while the overall number of high-confidence liquid cloud retrievals decreases steadily from the swath edge with relative azimuths larger than 90° to the other edge, the relative frequency of slopes facing toward and away from the Sun does not change much with view direction, probably because the observations are far from the solar plane.

[24] Finally, cloud side viewing is another mechanism of 3-D radiative effects that can potentially influence the view angle dependence of retrieved τ-values. The observations of *Minnis* [1989] indicate that cloud side viewing must occur quite frequently indeed, because it significantly increases cloud coverage for oblique views. Reflection into oblique directions is generally enhanced by the leakage of oblique radiation through cloud sides [e.g., *Davies*, 1978; *Kobayashi*, 1993; *Várnai and Davies*, 1999] while at the

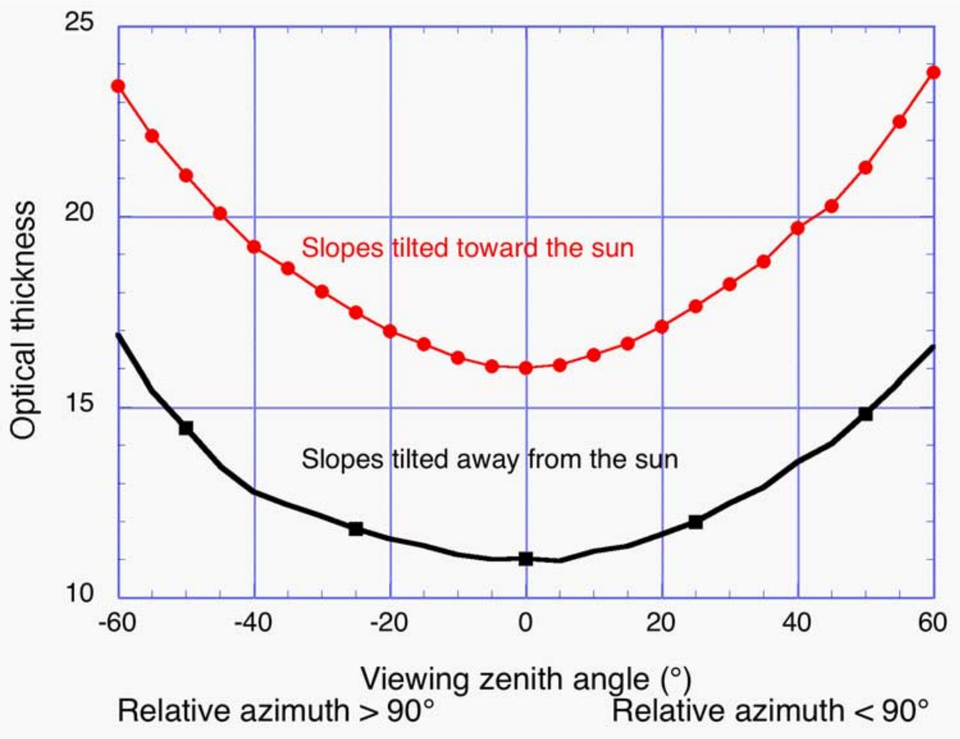

Figure 9. View angle dependence of τ for inhomogeneous pixels that lie on slopes tilted toward and away from the Sun ($T_f > T_b$ and $T_f < T_b$, respectively). The curves represent the average for five different solar zenith angle intervals ranging from 55 to 80°. The quadratic polynomial coefficients for slopes tilted toward and away from the Sun are $c = 2.05*10^{-3}$ and $1.53*10^{-3}$, respectively. *Várnai and Marshak* [2002a, 2002b] attributed the difference between the two slopes to 3-D radiative effects that enhance and reduce their illumination, respectively.

same time, this leakage reduces the amount of radiation available for nadir reflection, further deepening the U shapes in Figure 2b.

[25] Cloud side viewing can also cause the observed U shapes because while overhead views can see through small sub pixel gaps in cloudiness, oblique views tend to see cloud sides instead. This can result in stronger plane-parallel biases and thus stronger reductions in retrieved optical thicknesses for overhead views than for oblique views. Part of the enhanced τ-values at oblique view angles may also be explained by larger reflectances from cloud sides than from cloud top if the plane-parallel approximation was applied to cloud sides as vertically rotated plane-parallel clouds.

[26] It is important to note that although several observational studies [e.g., *Loeb and Davies*, 1997; *Buriez et al.*, 2001; *Horváth and Davies*, 2004; *Marchand and Ackerman*, 2004] found 3-D radiative effects reducing and enhancing cloud reflection in forward and backscatter directions, respectively, our results show similar optical thickness increases on both sides of swaths despite their azimuthal differences. This symmetry likely arises because, for oblique Sun, MODIS observations are limited to side scattering directions 60–70° away from the solar plane, whereas the reductions and enhancements are most pronounced closer to the solar plane. Indeed, theoretical simulations [e.g., *Davies*, 1984; *Bréon*, 1992; *Kobayashi*, 1993] indicate that horizontal photon transport can result in larger optical thicknesses being retrieved for the oblique views typical of MODIS observation geometry than for overhead views, even for relative azimuths less than 90°.

[27] In contrast to the observational studies mentioned above, the study of *Loeb and Coakley* [1998] did include observations at side scattering view directions similar to those in this study. They found that when the optical thicknesses retrieved for overhead views were used to predict cloud reflectances into oblique directions, the predicted values exceeded the observed ones for relative azimuths smaller than 90°. Considering that they analyzed marine stratus, the arguably most homogeneous cloud type, their results should be most comparable to the most homogeneous third of clouds in this study. Figure 2a, however, does not show significant decreases at oblique views for the solar elevations (~45°) considered by *Loeb and Coakley* [1998]. At this point it is unclear what differences in cloud properties, 1-D retrieval technique, or data analysis make homogeneous cloud reflectance follow 1-D theory more closely in this study than in the earlier one.

[28] One issue regarding side viewing is that this mechanism is present for all solar elevations, whereas Figures 2b and 4 show that the U shape is quite shallow for high Sun and its depth increases for oblique Sun. However, this behavior changes somewhat if we consider the difference between the cross-track behavior of inhomogeneous and homogeneous clouds by comparing Figures 2b and 2a, as this difference shows a pronounced U shape with a depth of $\Delta\tau > 3$ even for high Sun. Moreover, the enhanced

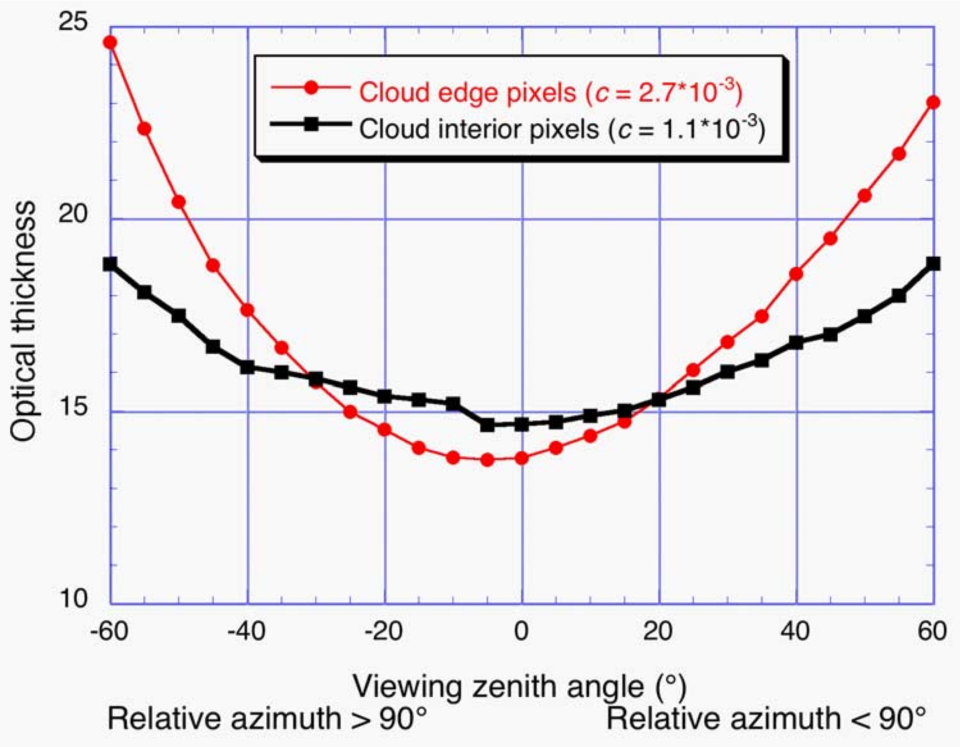

Figure 10. View angle dependence of mean optical thickness for inhomogeneous pixels that are surrounded by cloudy pixels or lie at cloud edges. The curves represent the average for five different solar zenith angle intervals ranging from 55 to 80°. Values of quadratic polynomial coefficient c are also displayed.

nonlinearity of 1-D reflectance versus τ curves at oblique Sun may allow inhomogeneity effects to have a stronger influence on retrieved τ-values for oblique Sun.

[29] Finally, Figure 10 reveals that the U shape is not limited to cloud edges: it is somewhat weaker but still clearly present at pixels that are surrounded by cloudy pixels on all sides. This is consistent with side viewing occurring not only at the edges of cloud cover, but also at small gaps in areas that appear overcast at 1 km resolution, at the sides of thicker cloud elements that are surrounded by thinner cloud portions, and at the edges of higher clouds located over lower-level clouds in multilayer situations.

6. Summary and Discussion

[30] This paper examined whether cloud inhomogeneity introduces any view angle-dependent biases into MODIS cloud optical thickness (τ) retrievals, which use the plane-parallel approximation and hence assume cloud homogeneity. The influence of cloud inhomogeneity was identified by contrasting the view angle dependence of mean τ values retrieved for clouds that were deemed "homogeneous" or "inhomogeneous" on the basis of the local gradient in 11 μm brightness temperature.

[31] The analysis of liquid phase clouds in a one yearlong global data set of Collection 4 MODIS cloud products revealed that while optical thickness retrievals give remarkably consistent results at all view directions for homogeneous clouds, they give systematically higher τ-values at oblique views than at overhead views for inhomogeneous clouds, especially if the Sun is fairly oblique. The mean optical thickness retrieved for the most inhomogeneous third of cloudy pixels is more than 40% higher for oblique views at swath edges than for overhead views at the swath center if the solar zenith angle exceeds 60°. The observations reveal that the dependence on view angle is stronger for higher clouds and for clouds over land, that it is present over a wide range of cloud thicknesses at both hemispheres through all seasons, and that it is similar in observations by the Terra and Aqua satellites.

[32] As the view angle dependence of retrieved τ-values can be approximated well using second-order polynomials, the quadratic coefficient of these polynomials can be used to characterize cloud inhomogeneity effects in a simple manner.

[33] After considering several potential scenarios, the paper concluded that the observed behavior is most likely caused by cloud inhomogeneities influencing 1-D cloud property retrievals, and not by other differences between homogeneous and inhomogeneous clouds that are unrelated to inhomogeneity itself (e.g., in microphysics). The paper discussed several mechanisms through which cloud inhomogeneity may influence the view angle dependence of retrieved τ-values. We found that the most likely candidate is the increased viewing of cloud sides from oblique directions. Leakage of photons through cloud sides enhances reflection into oblique directions, plus while cloudy pixels may contain small gaps among broken clouds in overhead views, these dark gaps tend to be filled by cloud sides in oblique views. The similar increase of retrieved

τ-values at the two swath edges is likely to come from MODIS observing predominantly side scattering at azimuths far from the solar plane.

[34] Although individual observations are clearly affected by view angle-dependent cloud inhomogeneity effects, it is not yet clear whether these effects lead to significant biases when observations from a variety of view directions are combined, for example in the Level 3 MODIS cloud products. The hope is that if the observed cross-track variations in retrieved optical thickness arise from a combination of underestimations at overhead views and overestimations at oblique views, the average results will be unbiased. If, however, results for either overhead or oblique views are more accurate, systematic overestimations or underestimations may occur when observations from all viewing angles are combined. Once the dominant mechanism responsible for the observed view angle dependencies is fully understood, it will be possible to determine whether it decreases τ-values for overhead views, increases them for oblique views, or both. The analysis of Collection 4 data indicates that the view angle dependence due to cloud inhomogeneity will be weaker for Collection 5 cloud products, which will not include pixels at cloud edges. We note, however, that the view angle-dependent biases discussed in this paper are only one component of the overall effect of cloud inhomogeneities, and other components, e.g., dependencies on illumination conditions, may also be important in a variety situations.

[35] The results presented here may help improve future versions of the τ-retrieval uncertainty estimates that will start accompanying MODIS cloud products in Collection 5. These uncertainty estimates consider only factors within a 1-D framework (such as uncertainties in calibration, in atmospheric correction, and in surface albedo), whereas our results suggest that identifying inhomogeneous pixels through local brightness temperature gradients could help incorporating view angle-dependent cloud inhomogeneity effects as well. This approach may eventually help correct for the observed view angle-dependent biases in both polar-orbiting and geostationary satellite images. Such corrections could be especially important for geostationary satellites because they view areas from constant view directions, and so averaging over many observations may not be able to remove potential view angle-dependent biases.

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