Anisotropy of water cloud reflectance: A comparison of measurements and 1D theory

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[1] Bi-directional reflectances of marine liquid water clouds, as measured by the Multiangle Imaging SpectroRadiometer (MISR), are compared with plane-parallel radiative transfer model calculations. We define an angular consistency test that requires measured and modeled radiances to agree within ±5% for all chosen view angles for the observations to be classified as plane-parallel. When all nine MISR angles are used at the full 275 m resolution, 1 in 6 pixels (17%) pass the test. There is a slight dependence on effective radius R_e, with R_e = 8 μm resulting in the highest pass rate. As the resolution is degraded, clouds appear more plane-parallel, and the passing rate increases to 38% at the coarsest 17.6 km scale. The passing rate quickly decreases as the number of angles used in the angular test increases. Requiring a match at only the nadir and two near-nadir angles immediately eliminates half of the full resolution pixels. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0394 Atmospheric Composition and Structure: Instruments and techniques; 1640 Global Change: Remote sensing. **Citation:** Horváth, Á., and R. Davies (2004), Anisotropy of water cloud reflectance: A comparison of measurements and 1D theory, *Geophys. Res. Lett.*, *31,* L01102, doi:10.1029/2003GL018386.

1. Introduction

[2] Due to its simplicity and computational speed, the plane-parallel radiative transfer model enjoys widespread popularity in the satellite remote sensing of cloud properties. This approach assumes locally one-dimensional clouds and, for visible radiances, a prescribed cloud droplet size distribution. Since 3D effects, such as cloud top structure, side illumination, and horizontal photon transport can cause significant departures from plane-parallel theory in realistic cloud fields [*Loeb et al.*, 1997], its applicability to global cloudiness may be limited.

[3] The performance of the plane-parallel radiative transfer model can be evaluated by comparing model generated bi-directional reflectance distributions with observations. Studies based on traditional single-view instruments, which lack the ability of capturing the instantaneous distribution of angular radiances, can offer only statistical comparisons with generic reflectance models composited from several different cloud scenes [*Stuhlmann et al.*, 1985; *Baldwin and Coakley*, 1991; *Loeb and Davies*, 1997]. Novel instruments, such as MISR and the Polarization and Directionality of the Earth's Reflectances (POLDER), on the other hand, provide near-simultaneous bi-directional reflectances, and therefore allow the evaluation of the plane-parallel assumption for individual clouds. The multiangle approach also holds the possibility of relaxing the condition of fixed cloud microphysics and directly retrieving the single scattering phase function [*Spinhirne et al.*, 1996; *Doutriaux-Boucher et al.*, 2000; *Parol et al.*, 2000].

[4] Some important constraints on the validity of the plane-parallel assumption have already been established. For example, *Doutriaux-Boucher et al.* [2000] found that due to the wide range of particle shapes and sizes, the modeling of ice cloud reflectance poses a much greater challenge than that of liquid clouds. Extended stratocumulus decks were found to behave, at least on average, like plane-parallel layers [*Descloitres et al.*, 1998]. Nevertheless, *Loeb and Davies* [1996] recommended that the application of the plane-parallel radiative transfer model should be restricted to moderate to high sun elevations and view angles in the backscatter direction. In addition, *Buriez et al.* [2001] pointed out the model's weakness in the rainbow and forward scattering directions.

[5] Most previous studies were restricted by coarse resolution or were limited to certain cloud types. The aim of our paper is to extend the analysis to a globally more representative, relatively high resolution data set. In the following, we try to quantify how frequently the plane-parallel radiative transfer model with fixed microphysics captures cloud anisotropy as measured by MISR and examine the effect of pixel resolution, effective radius, and number of measurement angles on the results. We limit the analysis to liquid clouds over ice-free oceans and note that data sampling is restricted by the instrument's mid-morning sun-synchronous polar orbit with an equator crossing time of 10:45 am.

2. Data and Methodology

[6] MISR on the *Terra* satellite measures reflected sunlight with nine pushbroom sensors oriented at different angles along track [*Diner et al.*, 2002]. The traditional nadir view is complemented by four pairs of oblique cameras positioned at nominal view zenith angles of 26.1°, 45.6°, 60°, and 70.5°. Each oblique pair consists of one camera looking forward and one looking backward, with respect to the direction of flight. Since the time interval between the

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two most oblique observations is 7 min, the instrument allows almost instantaneous sampling of the bi-directional reflectance field. The sampling, however, is limited to the nine fixed angles in a single azimuthal plane, determined by the flight direction with respect to the sun. Of the four available spectral channels, only the red band (672 nm) is used in this study since this offers the highest resolution. The cross-track resolution is 275 m, while the along-track resolution increases with view angle, from 214 m at nadir to 707 m at the most oblique angle. The along-track sample spacing, however, remains at 275 m.

[7] We used a total of 28 orbits from two particular days - orbits 6956–6969 acquired on April 9, 2001, and orbits 15330–15343 collected on November 5, 2002. Only maritime clouds between 60°N and 60°S were considered. Areas contaminated with sea ice were carefully removed from each orbit. Moderate-Resolution Imaging Spectroradiometer (MODIS, also on *Terra*) cloud phase data were remapped to the MISR swaths and used to filter out mixed phase and ice clouds. The red band spectral radiances were then corrected for Rayleigh scattering and ozone absorption. Rayleigh correction used the method outlined in *Wang and King* [1997] with remapped MODIS cloud top pressures as input. Ozone absorption cross sections provided by *Burkholder and Talukdar* [1994] were integrated over the MISR spectral response function and used in conjunction with remapped Total Ozone Mapping Spectrometer (TOMS) columnar ozone abundances. Gaseous absorption by other constituents, such as water vapor, was negligible.

[8] The measured anisotropy of cloud reflectance was then directly compared with plane-parallel calculations performed by the discrete ordinate code DISORT [*Stamnes et al.*, 1988]. No aerosols were included in the model and the ocean surface was assumed to be Lambertian with an albedo of 5%. To account for the inadequacy of the surface reflectance model, clouds with an optical thickness below 3 were excluded from the analysis. The single scattering phase function was obtained from Mie theory assuming a typical gamma droplet size distribution. In addition to our reference case with an effective radius of $R_e = 8$ μm, we also made calculations for $R_e = 5$ μm, and $R_e = 15$ μm.

[9] A simple angular consistency test was then applied to the data. A pixel passes our plane-parallel test if there is an optical thickness for which the measurements match plane-parallel radiative transfer model radiances at all angles within a given relative tolerance. The tolerance is arbitrarily set to ±5%, which is sufficiently larger than the 1% accuracy of the relative radiometric calibration of the nine cameras [*Bruegge et al.*, 2002]. An example is shown in Figure 1. In panel (a) a plane-parallel model cloud of optical thickness 37 fits the measurements reasonably well, and thus passes the test. In panel (b), however, the model cannot explain the observed cloud anisotropy within the retrieved optical thickness range of 15 to 40, and hence fails the test.

[10] We note here that coregistration of the multiangle views at cloud level poses a considerable challenge. There may be navigation errors, biasing our passing rates low at the highest resolutions (<1.1 km). More generally, parallax effects due to cloud height and motion have to be considered. Here we accounted for parallax by using the 70-km domain averaged winds and heights routinely obtained from stereo matching in the MISR wind retrieval algorithm

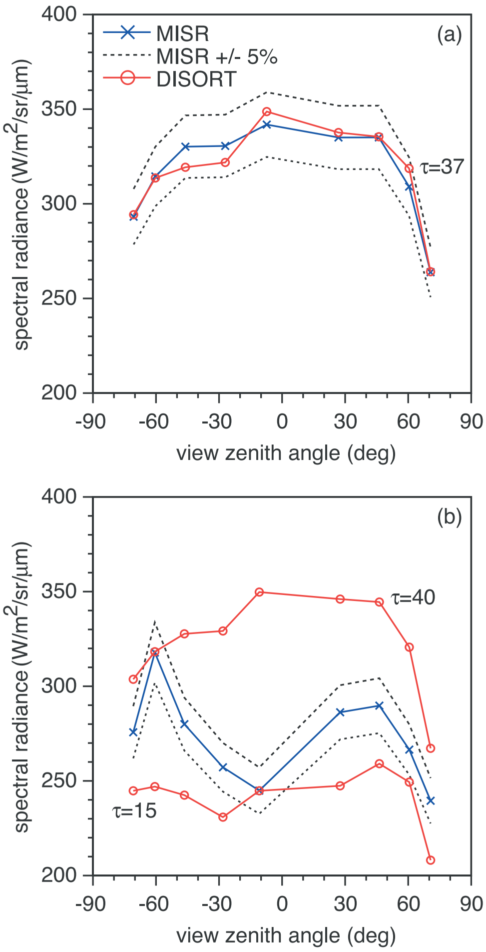

Figure 1. Comparison of measured and plane-parallel angular reflectances at a resolution of 275 m. (a) Cloud passes the angular test. (b) Cloud fails the angular test. Both examples are from block 118 (centered at 34°S, 113°E) of orbit 6156. The solar zenith angle is 33° and the measurements are approximately in the 40°/220° azimuthal plane. Data points with negative (positive) view zenith angles are in the forward (backward) scattering direction.

[*Horváth and Davies*, 2001], assuming constancy within each domain for computational expediency. The uncertainty due to this assumption was tested against the MISR operational reprojected radiances for cloud tops at a 2.2 km resolution and found to introduce an additional uncertainty in the passing rates of about 2% at that resolution. Combining sampling errors due to natural variability, the overall uncertainty in our passing rates is about 5% at 2.2 km resolution. The coregistration error decreases at coarser resolution, but may bias the passing rates low at the highest resolutions (<1.1 km).

3. Results

3.1. Dependence on Cloud Droplet Effective Radius

[11] Table 1 gives the passing rates, at 275 m resolution and averaged over the 28 orbits, for the three different effective radii we considered. In general, approximately one pixel in six passes our test. The best agreement between model and observations is obtained with an effective radius

Table 1. Average Passing Rate at a Resolution of 275 m vs. Effective Radius

Effective Radius	Passing Rate
5 μm	16%
8 μm	17%
15 μm	14%

of 8 μm, while a radius of 15 μm yields the worst results. Comparison of the passing rates for individual cloud scenes (not shown) reveals that in the vast majority of cases the 15 μm effective radius model is clearly less adequate than the 8 μm model. The 5 μm effective radius model, on the other hand, compares much more favourably with the 8 μm model, with only slightly smaller passing rates most of the time.

[12] The scarcity of well established global climatologies of cloud droplet effective radius makes it difficult to put the above results in perspective. The near-global survey of *Han et al.* [1994] estimated the mean effective radius as ~12 μm for marine clouds. This would imply that, on average, the angular reflectance pattern measured by MISR is more isotropic than the plane-parallel prediction corresponding to this global value. A possible explanation could be that cloud top structure makes reflected radiation more diffuse and less anisotropic compared to the plane-parallel radiative transfer model. In situ measurements [*Miles et al.*, 2000] and a global POLDER data set [*Bréon and Colzy*, 2000], however, suggest a typical cloud droplet effective radius that is a couple of microns smaller than the value of *Han et al.* [1994]. This is also more consistent with our findings. We note, however, that the effective radius that yields the highest passing rates is representative only of clouds that match the plane parallel model, and not necessarily representative of global cloudiness.

3.2. Dependence on Resolution

[13] Figure 2 shows the passing rate as a function of pixel resolution for our reference case (R_e = 8 μm). In general, clouds appear more and more plane-parallel as the resolution is degraded. However, even at the coarsest resolution of 17.6 km, no more than 38% of the pixels pass the angular consistency test. The better agreement, at coarser resolutions, between the 1D model and measurements might be due to the partial cancellation of 3D effects. For instance, sunlit and shadowy cloud sides are averaged together, and the net horizontal photon transport is decreased at lower resolutions.

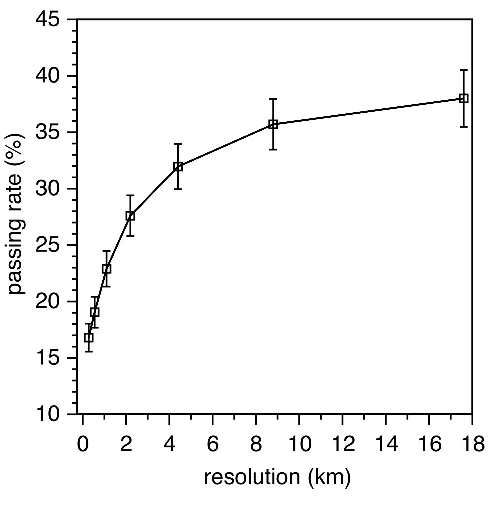

Figure 2. Angular test passing rate vs. pixel resolution for R_e = 8 μm. Error bars correspond to the standard error in the mean.

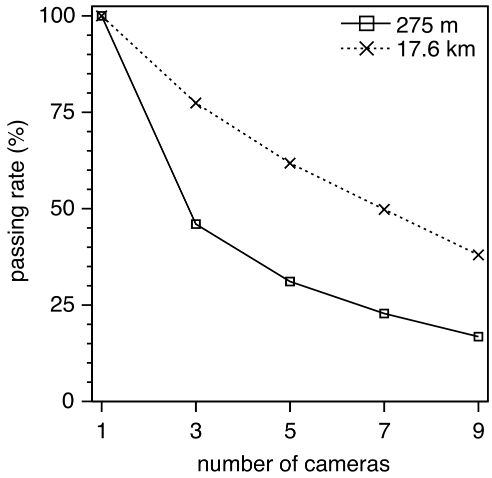

Figure 3. Angular test passing rate vs. number of cameras for R_e = 8 μm.

3.3. Dependence on Number of Cameras

[14] We also investigated how the results change as more and more oblique cameras are added to the angular test (see Figure 3). As expected, the passing rate decreases as the number of angles (at which matches between model and measurement are required) increases. The decrease is close to linear at the 17.6 km scale, while at the resolution of 275 m the largest change already occurs when two more cameras are used in addition to the nadir view. Adding the two near-nadir angles to the test eliminates half of the full resolution pixels.

4. Summary

[15] Multiangle radiances acquired by MISR have been analyzed to evaluate the validity of the plane-parallel cloud assumption. We devised a simple angular test that compares the measured cloud anisotropy with model predictions. At the 5% relative tolerance level only a modest percentage, 17% or 1 pixel in 6, of the highest resolution data pass our test. The results are calculated assuming constant cloud microphysics, tuned to give a maximum passing rate with an effective radius of R_e = 8 μm. Dynamic adjustment of cloud microphysics might give slightly higher passing rates.

[16] There is a clear dependence of passing rate on pixel resolution. The passing rate first increases as the resolution is degraded, then it levels off at larger spatial scales. Even at the coarsest resolution, no more than 38% of the pixels pass the angular test. While the passing rates at the highest resolutions (<1.1 km) have slightly higher uncertainty and a likely negative bias due to possible coregistration errors, the secular rise of passing rate with degraded resolution is not a coregistration issue. Rather, as the subpixel details of a scene become

averaged (cf. an out of focus image) the scene appears to behave more like a plane parallel one. Analogous resolution-dependent effects were noted earlier by *Di Girolamo et al.* [1998] and by *Oreopoulos and Davies* [1998].

[17] The fact that clouds are apparently more plane-parallel at larger scales, however, may be misleading. The suitability of the plane-parallel radiative transfer model does not imply that the retrieved cloud properties, such as optical thickness, are unbiased.

[18] Our angular heterogeneity results can be contrasted with the spatial heterogeneity study of *Genkova and Davies* [2003]. On a similar but larger MISR data set they found that, depending on the view angle, only 1–5% of all 8.8 km^2 cloud scenes passed their spatial homogeneity test. This and our significantly larger angular passing rates imply that an apparent match between observed and plane-parallel angular reflectances does not necessarily require spatial homogeneity, at least on an 8.8 km scale. The same qualitative result, i.e., a much larger spatial than angular variation of cloud optical thickness, was also reported by *Parol et al.* [2000] for POLDER data.

[19] We note in closing that the issues of coregistration, cloud microphysics, and sun-synchronous sampling may affect these passing rates by a percent or two here and there, but that the main conclusion seems inescapable. The vast majority of maritime liquid water clouds fail a simple 1D angular test at the ±5% level in radiance. The retrieval errors thus introduced cannot necessarily be expected to cancel, given the nonlinear dependence of reflected radiance on optical depth. Conversely, there is a significant subset (around 20%) of global cloudiness that passes the angular test and could be amenable to analysis by 1D theory with higher confidence perhaps. Such confidence would rest on the ability to identify the correct subset of clouds, as well as an understanding of the sufficiency of the angular test (deferred to a future study).

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