P2.5 ANGULAR VARIATIONS OF CLOUD PROPERTIES DERIVED FROM VIRS AND MODIS DATA FOR CERES

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1. INTRODUCTION

The Clouds and the Earth's Radiant Energy System (CERES) experiment utilizes broadband and narrowband scanners to obtain coincident measurements of broadband radiances and cloud properties from the same spacecraft. The high spatial resolution cloud properties allow for the development of improved bidirectional reflectance functions that in turn yield increased accuracy in earth radiation budget (ERB) products. The ERB improvements displayed by the CERES project are highly dependent on the accuracy of the narrowband cloud properties at all those angles.

The CERES instrument is currently flying aboard three satellites, Tropical Rainfall Measuring Mission (*TRMM*), *Terra*, and *Aqua*, launched in May 2002. *TRMM* flies in a precessing orbit with a 46-day repeat cycle while *Terra* is sun-synchronous with 1045 and 2245 local overpass times. *Aqua* is also sun-synchronous with 0130 and 1330 local overpass times, thereby completing the suite of measurements and allowing for extensive studies of cloud and radiative properties and their diurnal cycles. The narrowband instrument used to determine cloud properties from *TRMM* is the Visible and InfraRed Scanner (VIRS) while the MODerate-resolution Imaging Spectroradiometer (MODIS) is used for *Terra* and *Aqua* cloud properties.

The orbits of the CERES satellites provide coverage of nearly all viewing and solar zenith angles as well as many relative azimuth angles. This paper examines the dependencies of the CERES-derived cloud properties as a function of these angles to examine the effects of non-plane parallel clouds on retrievals that are based on plane-parallel models. These angular variations will be useful for understanding the effects of real clouds on an idealistic retrieval as in Loeb and Coakley (1998) and perhaps provide some means for correcting for the non-plane-parallel effects. The accuracies of the new CERES bidirectional reflectance distribution functions (BRDF) are directly impacted by these dependencies as is their application in the radiance-to-flux conversions.

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2. METHODOLOGY AND DATA

The 0.65, 1.6, 3.7, 11.0, and 12.0-µm channels from VIRS and MODIS are used to derive cloud properties with several multispectral techniques. Parameterizations of theoretical reflectance and emittance calculations are matched to observed satellite radiances for 7 water droplet and 9 ice crystal size distributions as described in Minnis et al. (1995; 1998). A Visible Infrared Solar-infrared Split-window Technique (VISST) and a Solar-infrared Infrared Split-window Technique (SIST) are applied at daytime and nighttime, respectively, to estimate cloud fraction, phase, effective particle size, optical depth, altitude, and ice/liquid water path. Additionally, techniques developed by Platnick et al. (2001) are adapted to the CERES framework resulting in a new analysis method, the Solar-infrared Infrared Near-infrared Technique (SINT) which is applied over snow- and ice-covered surface backgrounds during daylight hours (Young et al., 1999). The VIRS spatial resolution is 2-km at nadir while MODIS pixels are 1-km and subsampled to 2-km.

The CERES cloud property retrieval algorithm utilizes profiles of temperature, height, and ozone from 6-hourly European Center for Medium-Range Weather Forecasting (ECMWF) analyses. The 3-hourly ECMWF skin temperatures corrected to the top of the atmosphere with correlated k-distribution techniques (Kratz, 1995; Minnis et al., 1995) are used to predict clear-sky temperatures. Global monthly background maps of surface emissivity are constructed and utilized. Clear-sky reflectances are obtained from background albedo maps. Global clear-sky reflectance maps are continually updated to account for changes in surface characteristics, e.g., vegetation and moisture. Cloud identification for each pixel is accomplished using a series of cascading threshold tests in each wavelength (Trepte et al., 1999).

Cloudy pixels are assumed to be 100% cloud-filled and to contain one cloud layer. These assumptions and the usage of plane-parallel models introduce potential inaccuracies in the cloud property retrievals, but validation with surface-derived measurements has been encouraging. Dong et al. (2002) compared results from the same retrieval techniques applied to GOES data over the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains Central Facility and found reasonable agreement with surface-derived cloud optical depths, heights, and microphysical properties. Minnis et al. (2002) also found consistency between VIRS and MODIS results.

3. RESULTS

VIRS imagery from the *TRMM* satellite has been processed continually by the NASA Langley Atmospheric Sciences Data Center since January 1998. MODIS data from *Terra* were available beginning in March 2000 and *Aqua* data are expected in July 2002. The results below depict the angular dependencies for two months when results from both instruments were available, December 2000 and June 2001. The latest edition of MODIS processing software was not available until May 2002 resulting in the need to use means from one-week periods to represent monthly means. While this likely introduces some differences between VIRS and MODIS, the angular dependencies of MODIS can be considered representative of monthly results.

Another source of differences between VIRS and MODIS is their respective latitudinal coverage. *TRMM*'s precessing orbit allows VIRS to see only latitudes between 37ºS and 37ºN while MODIS scans the entire globe. The results presented in this preliminary study include the entire domain for each satellite, so should not be used for direct intercomparisons.

3.1 *Viewing Zenith Angle Variations*

Mean cloud fraction as a function of viewing zenith angle (VZA) for December 2000 is shown in Fig. 1. During both day and night, cloud amount increases noticeably with increasing VZA for both instruments. The VIRS and MODIS cloud amounts rise by 8% and 7.5% (absolute), respectively, over oceans during the day over the VZA range covered by both instruments. VIRS has a limited VZA range compared to MODIS, which scans to 68º. MODIS mean daytime cloud amounts increase an additional 5% for the VZA beyond the VIRS VZA cutoff of 48º. Over land during the day, the increase is limited to 3.2% for VIRS and 4.6% over all MODIS VZAs. At night over ocean, the respective increases are limited to 0.8% and 5.5% over the VIRS VZA range. Beyond 46º, MODIS cloud amounts increase by another 6.2%. Land regions for VIRS and MODIS during night time exhibit almost identical trends.

The increase in field-of-view size as the scanners see further from nadir is a major contributor to the cloud amount increases. To minimize these effects in the CERES cloud retrievals, a VZA-dependent infrared threshold was developed for use in the CERES cloud mask. If μ = cos(VZA) and the monthly average spatial and temporal variation of clear sky temperature for a given region is ΔTcs, then the predicted clear sky temperature threshold is

$$Tcs = \Delta Tcs + (8.22 - 15.37 \times \mu + 7.15 \times \mu^2) / 2.0.$$

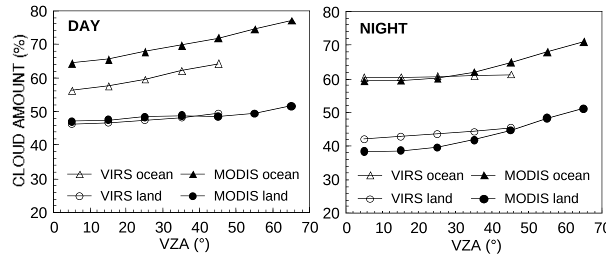

Fig. 1. VIRS- and MODIS-derived mean water and ice cloud amounts vs. viewing zenith angle (VZA) for December 2000.

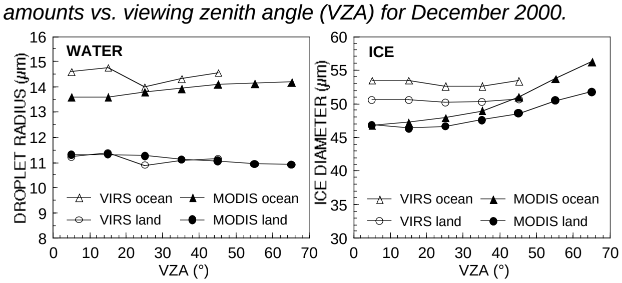

Fig. 2. Mean effective water droplet radius and ice crystal diameter vs. VZA for June 2001.

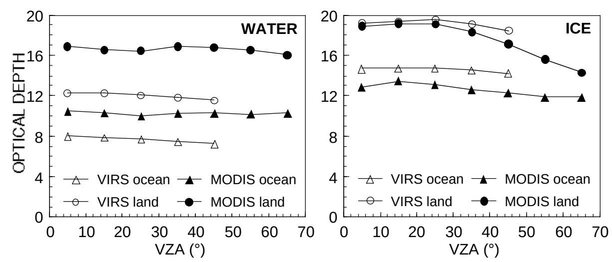

Fig. 3. Mean effective optical depth vs. VZA, June 2001.

This threshold, developed by examining several months of preliminary VIRS results, diminished but did not eliminate the cloud amount increase with VZA as evident in Fig. 1. Additional improvements are being explored; however, much of the increases can not be removed without eliminating bona fide clouds.

Figure 2 shows the effective water droplet radius r_e and ice crystal diameter D_e variations with VZA for daytime during June 2001. The trends for VIRS are almost negligible with the exception of a small decrease of less than 1.0 µm in r_e over ocean and land that peaks in the 20º to 30º VZA bin. MODIS water droplet radii show small variations (< 0.5µm) over both land and ocean. As with water droplets, the VIRS D_e shows no significant trend while the MODIS D_e increases with increasing VZA. The MODIS results need additional scrutiny.

For both instruments optical depth drops slowly with increasing VZA as shown in Fig. 3. For the VIRS VZA range, the drop for both VIRS and MODIS varies from about 6% to 9% over water and from about 3% to 4% over land. Over the larger MODIS VZA range, optical depth retrievals over land decrease by as much as 24% while over ocean, the decrease is only an additional 2% to 5% in the higher VZA bins.

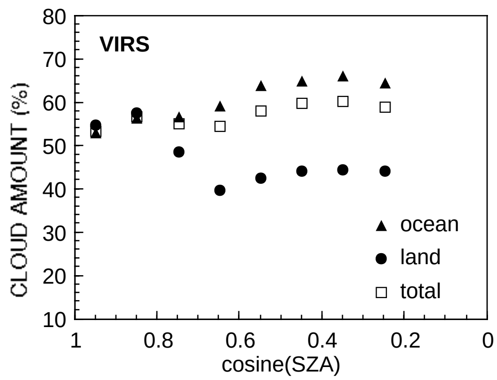

Fig. 4. December 2000 VIRS-derived mean cloud amounts vs. cosine solar zenith angle (SZA) for different backgrounds.

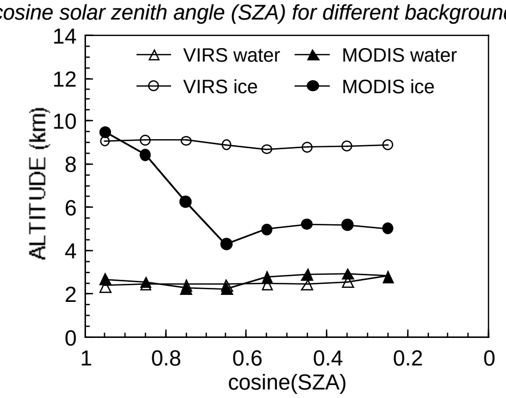

Fig. 5. June 2001 VIRS- and MODIS-derived mean water and ice cloud heights vs. cosine SZA.

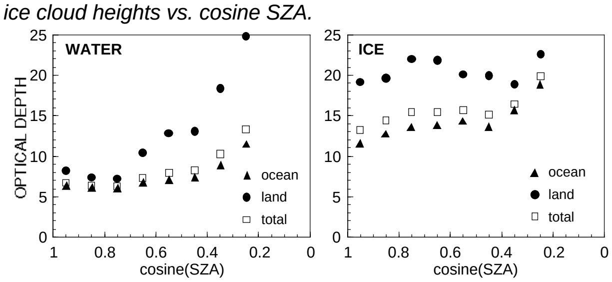

Fig. 6. June 2001 VIRS-derived water and ice cloud optical depths vs. cosine SZA for different backgrounds.

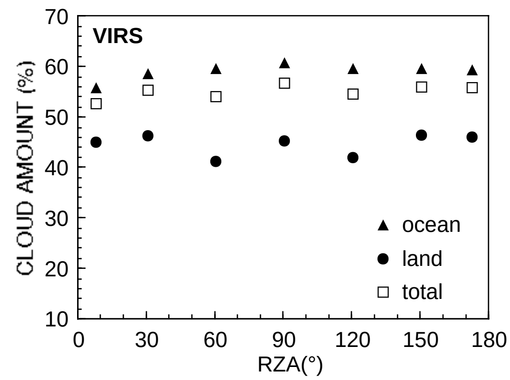

Fig. 7. June 2001 VIRS-derived water and ice cloud optical depths and particle sizes vs. relative azimuth angle (RZA).

3.2 *Solar Zenith Angle Variations*

Variations of cloud properties with solar zenith angle (SZA) are plotted as functions of cos(SZA) in Figs. 4, 5, and 6. Figure 4 shows an 8% (absolute) increase in cloud fraction over the range of SZA for the December 2000 retrievals over ocean. Land cloud amounts appear to decrease by as much as 17.8% from a peak of 57.8% at cos(SZA) = 0.85 with total amounts following the ocean trends due to the large amount of ocean area observed from *TRMM*. The odd SZA variation of clouds over land may be consistent with the average diurnal variations of cloud cover over land. The Terra orbit was selected in part because of minimum in cloud fraction over land around 1030 LT. Additionally, maximum cloud cover occurs between 1200 and 1500 LT during December for most land regions observed by VIRS (Warren et al. 1986). Over oceans, stratus cloud cover often peaks during the early morning and rebuilds during the late afternoon, a cycle that is consistent with the SZA variation in Fig. 4.

During June 2001, both VIRS and MODIS water cloud heights (Fig. 5) exhibit very little functionality with SZA. VIRS ice cloud heights also show only a small decrease with increasing SZA that bottoms in the 50º to 60º SZA bin. The large range of MODIS-derived ice cloud heights (~5 km) is due primarily to the sampling pattern of MODIS. Large SZAs correspond to near-polar latitudes where the tropopause is much lower than over the Tropics and ice clouds form at lower altitudes.

In Fig. 6, the increase of VIRS optical depth with increasing SZA is evident, particularly for water clouds over ocean and land which increase almost 200% and 300%, respectively, from overhead sun to near the terminator. Ice cloud optical depth over ocean increases on the order of 150% while over land a trend is not discernable. A combination of factors may be contributing to these large variations, including diurnal cycles in cloud liquid and ice water amounts, 3D effects, and clear-sky reflectance variations, i.e., sunglint. Examination of these effects is ongoing.

3.2 *Relative Azimuth Angle Variations*

Figure 7 shows the relative consistency of cloud amounts with relative azimuth angle (RZA) for VIRS retrievals for June 2001 over all background types. There are cloud amount minima over land of 3% to 5% (absolute) in side-scattering conditions. Minimum cloud amount over ocean occurs near RZA = 0°, probably as a result of the confusion caused by sunglint. The variations of optical depth and particle size with RZA are shown in Fig. 8. Water cloud optical depths have a minimum at backscatter angles and a maximum in the forward scatter direction. Ice clouds show a maximum in backscatter and a minimum in side scatter conditions with a $\pm$12% variation. Fig. 8 also shows very small variations of particle size with RZA, including a $\pm$5% change in r_e and a $\pm$4% in D_e. These small variations of particle sizes an optical depths provide a measure of accuracy for the models and retrieval methods used by CERES.

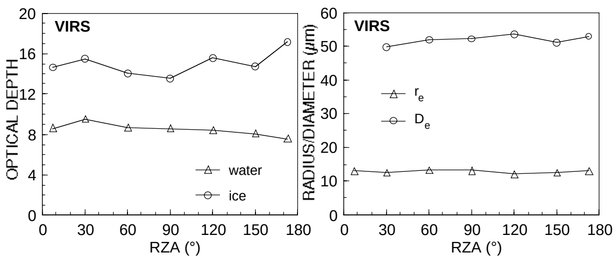

Fig. 8. June 2001 VIRS-derived cloud amount and vs. relative azimuth angle (RZA) for different backgrounds.

4. DISCUSSION AND SUMMARY

This first examination of the angular dependencies of CERES cloud properties shows mostly consistent results between VIRS and MODIS while revealing some large variations in cloud properties, particularly with solar zenith angle. Most of the disagreements between retrievals from the two instruments can be attributed to time sampling and coverage differences as well as the fact that the MODIS results for December 2000 and June 2001 are for one week only.

Variations of cloud amount, particle size, and cloud height with all angles are generally acceptable although further improvements may be possible. Cloud amount dependencies on VZA have been reduced somewhat using an improved threshold technique but they are a given because of the impact of viewing cloud sides in partly and mostly cloudy conditions. The variation of cloud amount with SZA may be due to the diurnal cycles of cloud cover and require additional examination. In general, particle sizes for water and ice show reasonable variations with all angles except for MODIS sizes which increase faster with VZA than for VIRS.

The increase of optical depth for water clouds, regardless of background surface, and for most ice clouds, is likely due to a combination of effects. Future work will include the creation of bidirectional looks at optical depth that should reveal more detail. While and the limitation of 1D radiative transfer theory is a primary candidate for the larger variations, other effects are likely playing a role. Cloud aspect ratio could impact cloud detection and cloud height, including any preferred angular orientations with latitude or regime. The inability of MODIS onboard Terra, or any sun-synchronous satellite, to detect large portions of diurnal cycles also could induce variations.

Future investigation of these dependencies will include improved spatial matching of the VIRS and MODIS data as well as increasing the number of months in the analysis. When the angular dependencies are pinpointed further, individual coincident VIRS and MODIS scenes, rather than monthly average quantities, will be examined. The impact of angular dependencies on the CERES BRDF is the motivation for these studies, so the BRDFs themselves will be examined for any functionalities that are not revealed by studying the imager-derived cloud properties. An integrated look at both the BRDFs and the cloud properties should result in established error estimates and the opportunity to further improve the radiance to flux conversion process for CERES.

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