CIMEL Measurements of Zenith Radiances at the ARM SGP Site

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Introduction

The objective of our study is to exploit the sharp spectral contrast in vegetated surface reflectance across 0.7 μm wavelength to retrieve cloud properties from ground-based radiance measurements. Based on this idea, we have developed a new technique to retrieve cloud optical depth in the simultaneous presence of clouds and green vegetation, using ground zenith radiance measurements in two narrow spectral bands on each side of the step-function in vegetation albedo near 0.7 μm. Starting from October 1, 2001, Cimel at the Atmospheric Radiation Measurement (ARM) Central Facility in Oklahoma has been switched to a new "cloud mode." This mode allows taking measurements of zenith radiance when the sun is blocked by clouds. In this abstract, we show Cimel's zenith radiances together with Multi-filter Rotating Shadowband Radiometer (MFRSR) downward fluxes. The retrieved optical depth will be compared with cloud liquid water path (LWP) retrieved from Microwave Radiometer (MWR). Finally, we discuss the use of surface albedo from Moderate-resolution Imaging Spectroradiometer (MODIS) data.

CART Cimel as a Part of the AERONET

Cimel at the ARM CART site is a part of the AErosol RObotic NETwork (AERONET) - a ground based monitoring network that consists of identical multi-channel radiometers for assessing aerosol optical properties and validating their satellite retrievals (Holben et al. 1998). We have developed a method for

Cimel's to monitor cloud optical depth by using "idle time" inappropriate for aerosol studies for taking measurements of zenith radiance at 440, 670, 870, and 1020 nm. Every 13 min., if the sun is blocked by clouds, the Cimel points straight up and takes 10 measurements with 9 sec. time interval.

To illustrate this, Figure 1 shows aerosol optical depth downloaded from the AERONET database (http://aeronet.gsfc.nasa.gov:8080/). It was retrieved from the ARM CART site Cimel on October 15. We see two gaps caused by clouds: from 15:30 to 17:30 and 17:30 to 19:30 in GMT. A set of images from the Cloud and Radiation Testbed (CART) site Total Sky Imager (TSI) demonstrates broken cloudiness, clear sky and overcast sky from 14:00 to 19:30 Greenwich Mean Time (GMT).

Figure 2 shows Cimel's zenith radiance data collected from the same day. We see these measurements filing the gaps in Figure 1. Panel b is just a 20-min. zoom illustrating the frequency of measurements. Finally, panel (c) shows zenith radiance from panel (b) normalized by the extraterrestrial solar flux in the corresponding spectral interval. Note that the order of curves in panel (c) has been changed compared to panel (b): radiances in channels 870 and 1020 nm, and also in 670 and 440 nm, are close; this indicates cloudy conditions and the spectral contrast in surface albedo that dominates over Rayleigh and aerosol effects.

The effect of surface albedo can also be observed analyzing MFRSR data. Figure 3 shows two 30 min. fragments from November 13, 2001, with normalized flux measurements from MFRSR and normalized radiance from Cimel. The first fragment corresponds to a cloudy sky while the second one to cloudy with a transition to clear. We see that for a clear-sky, because of Rayleigh scattering, we have (panels [c] and [d]),

$$I_{440} >> I_{670} \approx I_{870} \approx I_{1020} \tag{1a}$$

$$F_{500} > F_{673} \approx F_{870}. \tag{1b}$$

By contrast, for cloudy conditions (panels [a] and [b]),

$$I_{440} \approx I_{670} < I_{870} \approx I_{1020} \tag{2a}$$

and

$$F_{500} \approx F_{673} < F_{870}. \tag{2b}$$

Normalized Difference Cloud Index

In contrast to any conventional method of estimating cloud optical depth from the surface that uses only one wavelength and is expected to work well only for overcast clouds, the new method is much less sensitive to cloud structure since it eliminates downward radiation for a "black" surface that is very sensitive to both illumination conditions and cloud inhomogeneity (Marshak et al. 2000, Barker and Marshak 2001). It can be shown that for clouds thicker than optical depth 10-20, the NDCI is almost

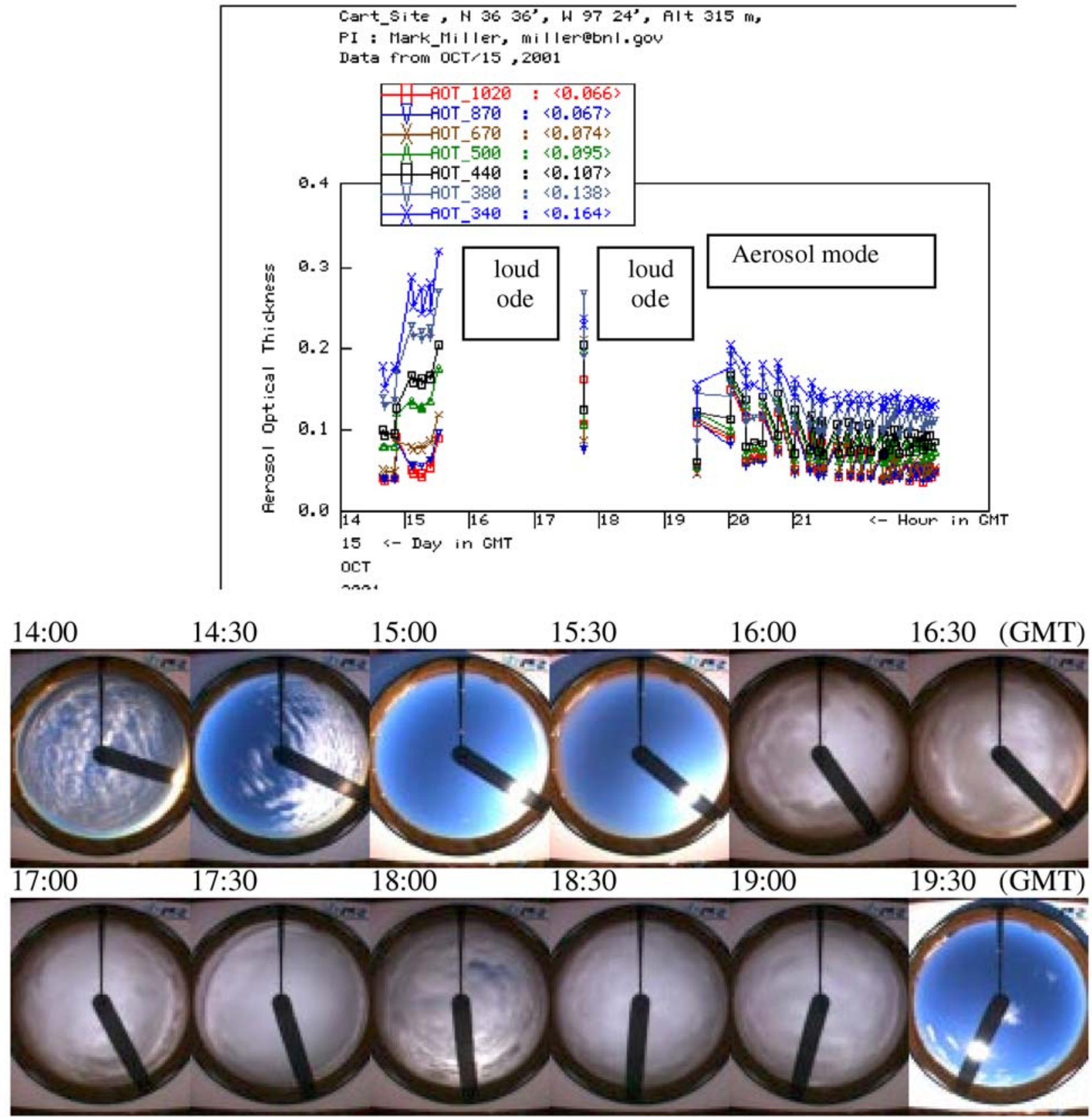
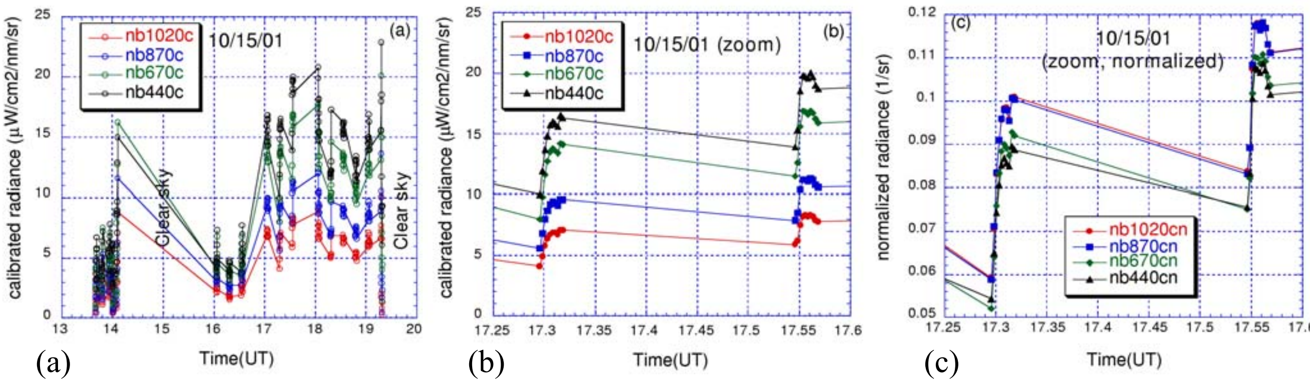


Figure 1. Aerosol optical depth at ARM CART site in Oklahoma on October 15, 2001 from the AERONET database. Note that on that day the Cimel radiometer worked in a cloud mode measuring zenith radiance before 14:30 and between 16:00 and 19:30 GMT. Twelve lower images are from the ARM CART site TSI taken every half an hour starting from 14:00 GMT.



(a) (b) (c)

Figure 2. Cimel's "cloud mode" data. (a) Cimel zenith radiance measurements at the ARM CART site on October 15, 2001. (b) A 20-min. zoom from panel (a) showing typical frequencies of measurements. (c) Zenith radiance from panel (b) normalized by the extraterrestrial solar flux in the corresponding spectral interval.

insensitive to the solar zenith angle (SZA); as a result, cloud optical depth for SZA=75° can be retrieved as well as for SZA=45°. This is very important because most current retrievals fail to produce reliable values of cloud optical depth for large SZA. A weak sensitivity of the NDCI to the SZA follows from the fact that our retrieval is based on surface-cloud interactions that do not strongly depend on SZA.

Figure 4 illustrates NDCIs for downward flux from MFRSR and for zenith radiance from Cimel. We see good agreement for an overcast sky (from 16:00 to 19:00 GMT) but rather poor for broken clouds (from 13:30 to 14:20). Measurements of downward flux yield additional information on cloud fraction and thus on the amount of radiation reaching the surface. This information can never be obtained using zenith radiance only. Obviously, knowledge of downward fluxes improves the retrieved values of cloud optical depth, especially for broken cloud conditions. Barker and Marshak (2001) suggested a new retrieval method that in addition to zenith radiance uses downward fluxes at both 670 and 870 nm. Pavloski et al. (2002) applied both methods to retrieved cloud optical depth using the newly developed Penn State dual narrow field-of-view, hemispherical spectrometer.

Surface Reflectance

Since the retrieval algorithm is based on surface-cloud interaction, knowledge of vegetation reflectances and their heterogeneity around Cimel is absolutely crucial for the success of the algorithm (see Figure 5, that illustrates NDCI versus cloud optical depth for different surface albedos, α.)

Figure 6 shows surface albedo calculated as a ratio between upwelling fluxes measured by Multi-Filter Radiometer (MFR) located at the 10-m and 25-m altitude of the tower at the ARM CART site and downwelling fluxes from the MFRSR. We see that at least for 870 nm, surface albedos estimated from 10 m and 25 m are substantially different: 0.28 for 10 m versus 0.31 for 25 m radiometers. The difference is likely due to green vegetation located away from the tower and hence not seen by the 10 m MFR. Such uncertainties in surface albedo may result in biased values of the retrieved cloud optical depth.

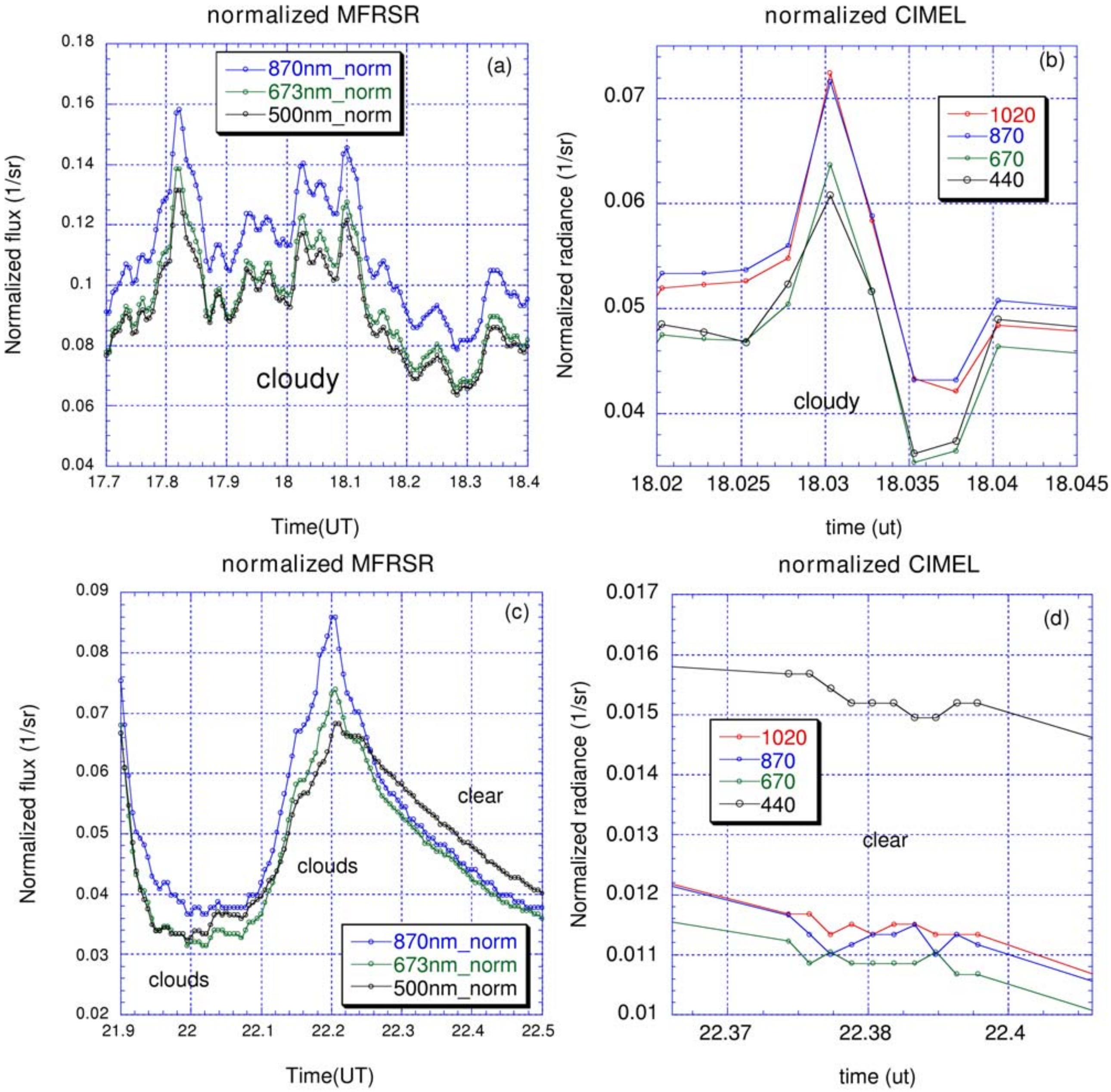


Figure 3. Normalized MFRSR's flux versus normalized Cimel's radiance for November 13, 2001.

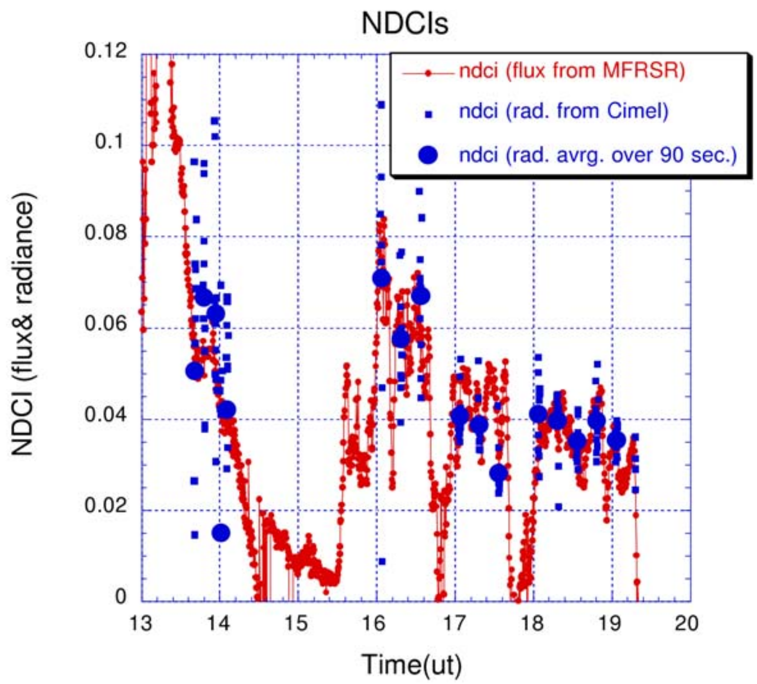


Figure 4. NDCI for flux (from MFRSR) and radiance (from Cimel), October 15, 2001. In addition to instantaneous measurements of zenith radiance, averaged over 90 sec. are also plotted.

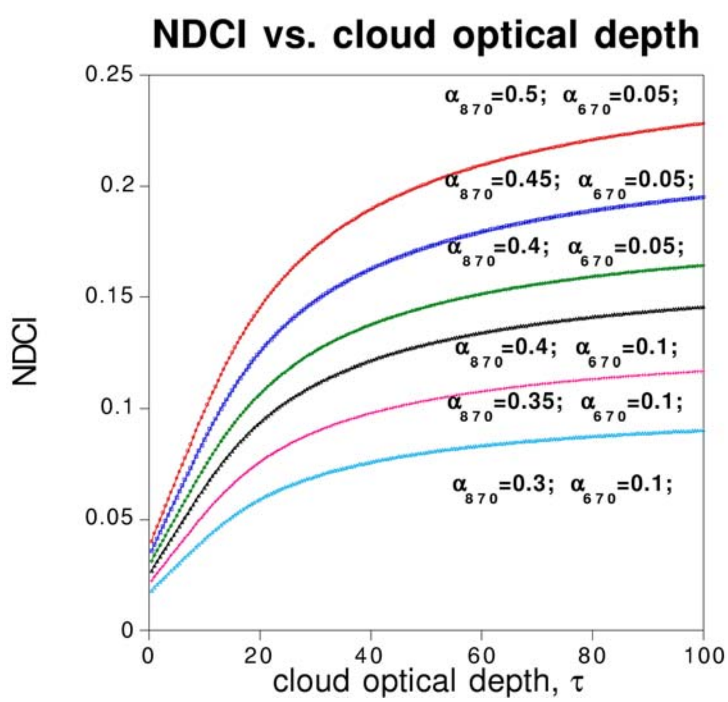


Figure 5. NDCI versus cloud optical depth for different surface reflectances calculated using DISORT (Stamnes et al. 1988).

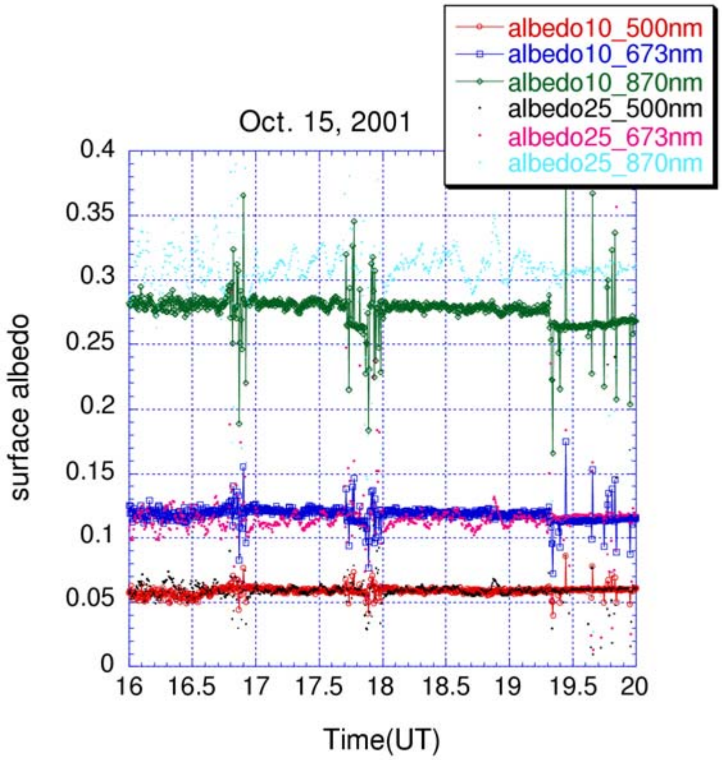


Figure 6. Surface albedo obtained from two MFRs located at 10 m and 25 m. Three channels: 500, 673, and 870 nm are plotted.

To estimate surface albedo we attempted to use MODIS data averaged over 16 days. Figure 7 illustrates surface albedo for 670 and 870 nm around the ARM Cart site. The average values are about 0.15 for 670 nm and 0.3 for 870 nm; they are consistent with MISR data (Pavloski et al. 2002).

For the theoretical study based on cloud fields inferred from Landsat imagery, Baker and Marshak (2001) found that as long as the uncertainties in surface albedo have the same sign (both are either overestimated or underestimated), the algorithm performs well. Furthermore, when the 870 nm albedo is overestimated but 670 nm albedo is underestimated, errors in the retrieved optical depth are not severe. However, in the opposite case, the algorithm underestimates multiple reflectance in the bright band and greatly overestimates optical depths.

Cloud Optical Depth Retrieval

Based on the 16-stream version of DISORT (Stamnes et al. 1988), we built a look-up table of NDCI versus cloud optical depth similar to Figure 5. Figure 8a compares cloud optical depth retrieved from Cimel zenith radiance using surface albedos 0.15 (670 nm) and 0.3 (870 nm) with cloud optical depth retrieved from MWR assuming droplet effective radius of either 10 or 15 μm. We see that the retrieved from Cimel values of optical depth are in good agreement with those retrieved from MWR. In addition,

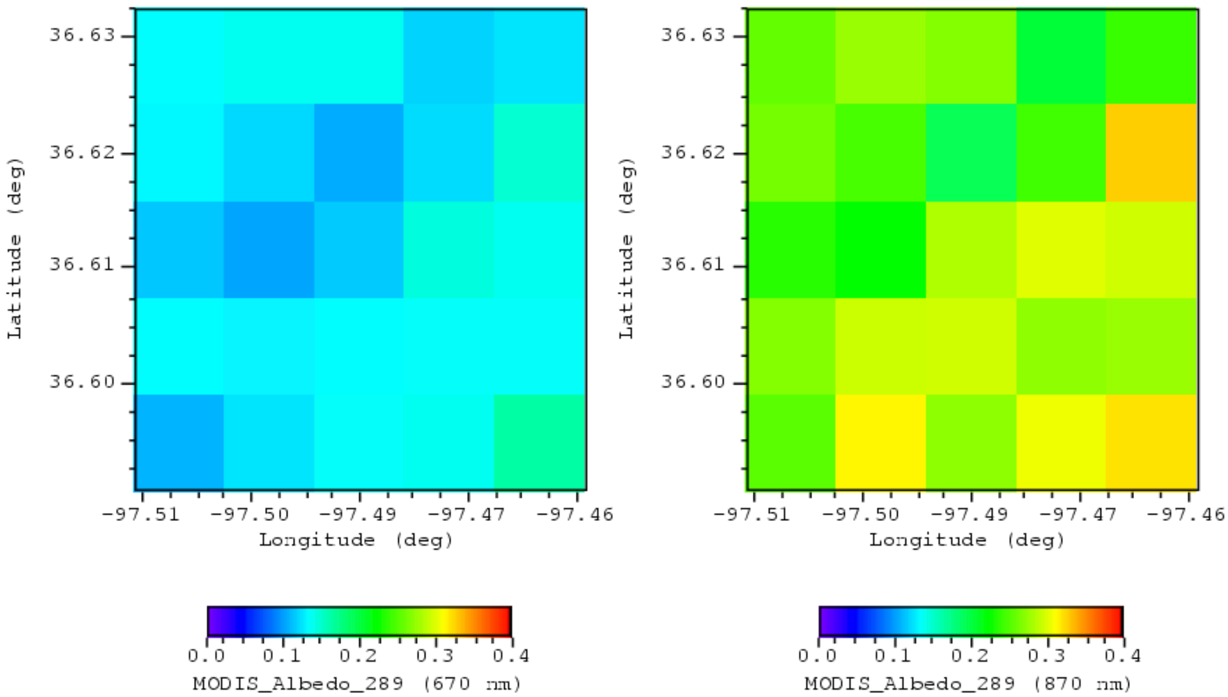


Figure 7, MODIS surface albedo at 670 and 870 nm. (a) Averaged over 16 days from October 1 to October 15, 2001. ARM CART site is in the middle. Each pixel is approximately 1x1 km. Images are supposed to be tilted left, i.e. longitude at the upper horizontal axis starts from –97.54°.

Figure 8b illustrates the values of cloud optical depth retrieved from Cimel for the overcast day of November 13, 2001. They are compared with those retrieved from MWR assuming droplet effective radius of 10 µm. No Cimel aerosol measurements were reported that day.

Conclusion

The NDCI method

- theoretically, looks promising; it is not a final answer but a big improvement against single-wavelength retrievals;
- uses CIMEL's idle time that is inappropriate for aerosol measurements;
- if successful, can fill (cloud) gaps in AERONET aerosol optical depth retrievals;
- combined with flux measurements at the ARM site gives more robust cloud optical depth retrieval;
- very sensitive to surface albedo; local surface albedo is not enough; satellite surface albedo is an improvement but has other drawbacks.

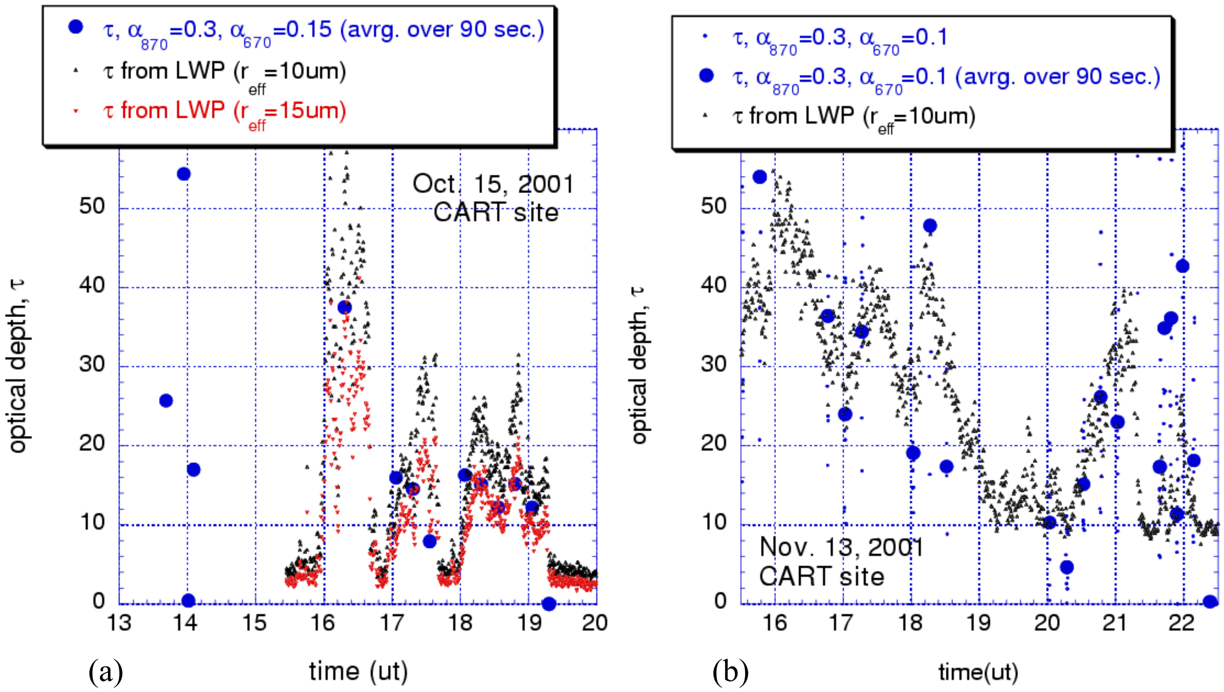


Figure 8. Comparison of the optical thickness values retrieved from Cimel and MWR. (a) October 15, 2001, based on surface albedo 0.3 (870 nm) and 0.15 (670 nm). MWR retrieved optical thickness assumes droplet effective radius equal to 10 or 15 μm, respectively. No MWR measurements were available before 15:50. (b) November 13, 2001 based on surface albedo 0.3 (870 nm) and 0.1 (670 nm). MWR retrieved optical thickness assumes droplet effective radius equal to 10 μm.

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