Cloud Optical Property Retrieval Over ARM Sites from Landsat

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Introduction

Cloud optical property retrieval is one of the main objectives of the Earth Observing System (EOS) (Wielicki et al. 1995), and the improvement of the algorithms developed to accomplish this objective is an area of active research. With the recognition in recent years of the influence of three-dimensional (3-D) radiative transfer on cloud retrievals, interest on the measurements of the thematic mapper (TM) radiometer aboard the Landsat satellite has been renewed. This instrument provides a unique high-resolution dataset where the effects of 3-D cloud structure are prominent. Attempts to include these in optical property retrievals have been scarce and only on limited datasets (e.g., Barker and Liu 1995). The common approach instead is to use the independent pixel approximation (IPA) (Wielicki et al. 1990, Harshvardhan et al. 1994), which neglects horizontal photon transport. Marshak et al. (1998) have shown that a consequence of this simplified approach, at least at high sun, is the underestimation of optical depth variability.

In this paper, we show Landsat IPA retrievals and their limitations over the Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) site, observational and modeling evidence of radiative smoothing, and discuss the potential of using the inverse nonlocal IPA (NIPA) of Marshak et al. (1998) to improve our retrievals.

Landsat IPA Retrievals

The Landsat scene available over the ARM SGP site was for 9/24/96, 16:25 GMT. The solar zenith angle (SZA) is ~45°. The scene covers an area of ~196 km^2 x 185 km^2 at a resolution of 28.5 m (6888 x 6489 pixels). Visible optical depth (τ), effective radius (r_e), and liquid water path (LWP) were retrieved for pixels classified as cloudy using a combination of thresholds. The procedure basically involves simultaneous minimization of band 2 (0.55 μm) and band 7 (2.2 μm) radiances from modeled values calculated from a modified version of Tsay et al.'s (1990) unified model. The cloud model assumed a lognormal dropsize distribution with effective radii ranging from 4 μm to 25 μm and effective variance of 0.13. The following table shows various inputs and assumptions.

	Band 2	**Band 7**
gases	O_3 (midlat.)	H_2O (obs.)
Rayleigh	Yes	No
aerosols	No	No
sfc. albedo	0.1	0.3
ice cloud	No	No
filter function	8 wavelengths	8 wavelengths

Figure 1 shows histograms of retrieved τ, r_e, and LWP = $2/3\tau r_e$. The zero bin indicates clear skies, the -1 flag corresponds to the saturated (at band 2) fraction, and the -2 flag is assigned to pixels which, while classified as cloudy, have band 7 reflectances smaller than the minimum value of the lookup tables. The band 7 discrepancy almost always occurs at cloud edges, thus illustrating a direct influence of geometric cloud effects. The τ distribution (Figure 1a) is not as skewed as in previous Landsat studies (Barker et al. 1996, Harshvardhan et al. 1994), while the r_e distribution (Figure 1b) is wider than those shown by Nakajima et al. (1991), and Platnick and Valero (1995). It should be noted, however, that all the above studies were conducted for oceanic boundary-layer clouds. A secondary peak for r_e = 25 μm may indicate the presence of droplets with r_e > 25 μm, or ice crystals. The LWP maxima (Figure 1c) do not exceed some of the maxima shown by Nakajima et al. (1991) for marine stratocumulus. The surface microwave radiometer (MWR) at the SGP site reports, around the time of the satellite overpass, much smaller values, more consistent with what we retrieve for the topmost 2000 scanlines (which contain the instrument site) of the Landsat scene (Figure 1d). A sensitivity study is currently under way to quantify the errors due to our assumptions and the uncertainty of the inputs in the look-up table calculations. We are also examining whether choosing a different pair of channels has a significant impact on the retrievals.

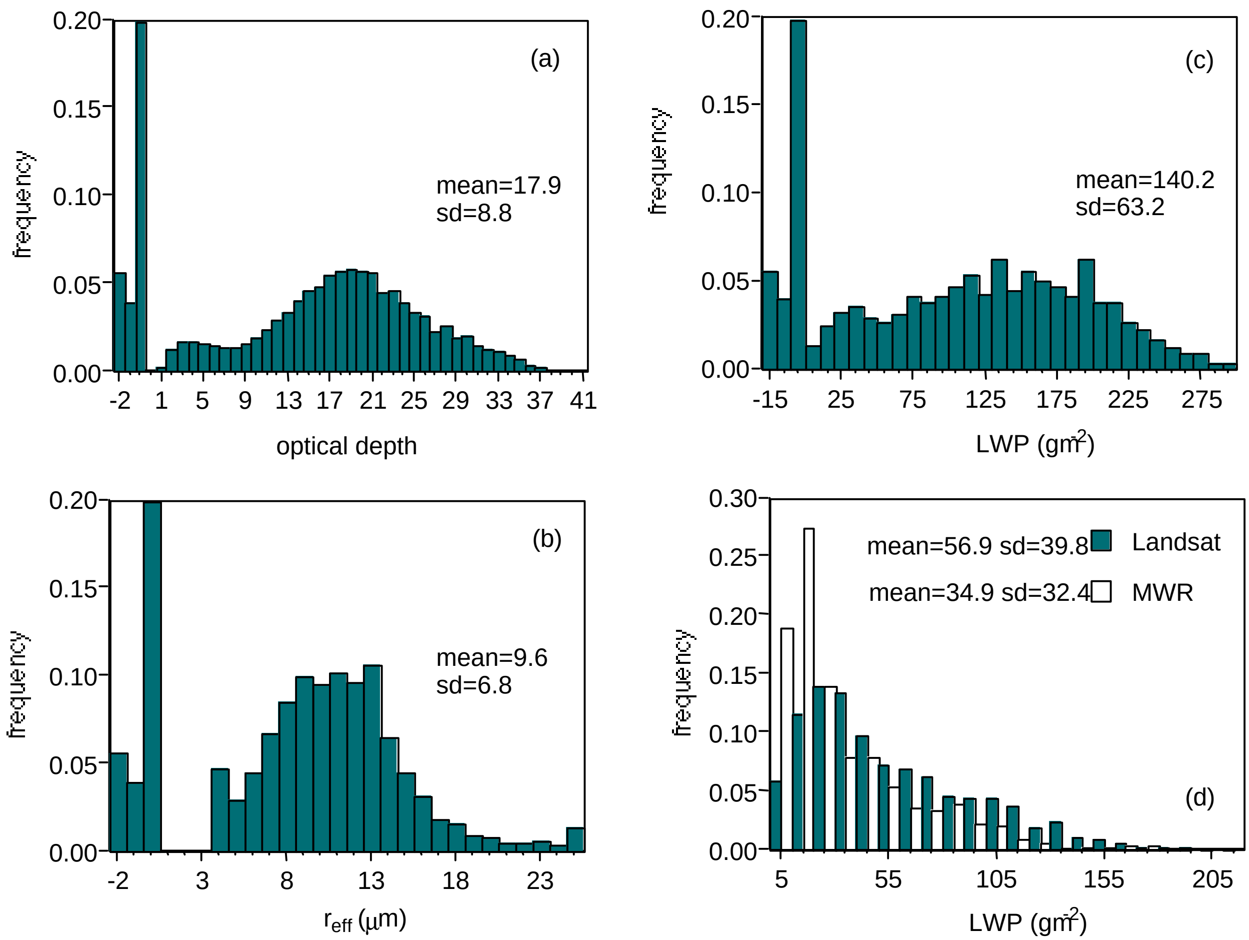

Figure 1. Histogram of retrieved cloud properties for Landsat scene (a,b,c), and comparison with MWR data around satellite overpass using top 2000 scanlines (d). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/oreopoulos-98.pdf*.)

While we are not ready to provide at present quantitative estimates of the influence of radiative smoothing on our retrievals, we can show an example of observational evidence of smoothing from power spectra calculated for an overcast portion of the scene (Figure 2b). The smoothing manifests itself as a change in the slope of the power spectrum at small scales, with the location of the slope break being wavelength-dependent. The absorbing wavelength also shows evidence of "radiative roughening" at intermediate scales as predicted by Várnai (1998). We were able to qualitatively reproduce power spectra similar to the observed (Figure 2a) with Monte Carlo (MC) simulations on simple (no cloud top variability, no vertical extinction profile) fractal bounded cascade clouds (Cahalan et al. 1994).

NIPA Modeling

NIPA is a potential tool for improving Landsat and other high-resolution cloud retrievals. The main idea is to remove the radiative smoothing due to horizontal photon transport (evidence of which is shown in Figure 2), so that IPA can be used for radiance inversion. At its present stage of development, NIPA can deal only with high ($\mu_0 > 0.85$) Sun cases where azimuthal dependence is not as important. Therefore, application of the NIPA transformation on the Landsat radiances of the SGP scene is left as a future exercise. We will instead focus here on MC simulations and will examine whether NIPA improvements on retrieved τ fields results in significantly improved radiation fields at different scales.

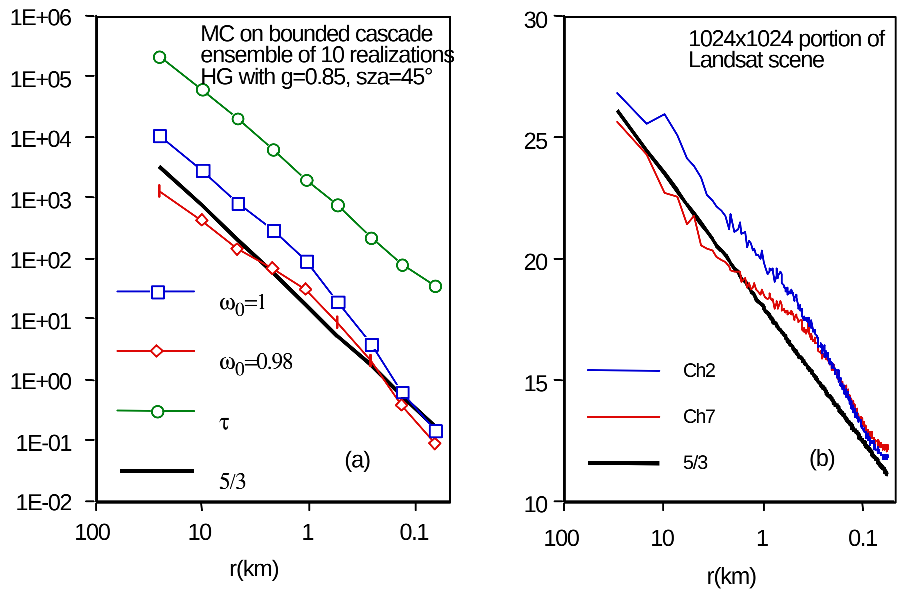

Figure 2. Nadir reflectance power spectra from MC (left) and Landsat (right). MC spectra are octave-binned. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/oreopoulos-98.pdf*.)

Retrieval of optical depths from MC radiation fields using the inverse NIPA requires the following steps:

1. Find optimal parameters α,η of the cloud field's Green function (see Marshak et al. 1995 for the physical meaning of α, and η); this step is easy when true cloud field is known since the α,η space can be scanned for the values where direct NIPA and MC radiation differences (at the pixel scale) are minimized.

2. Invert $R_{mc}=R_{ip}*G(\alpha,\eta,x)$

$$R_{ip}=\int \frac{R_{mc}(\mathbf{k})}{G(\alpha,\eta,\mathbf{k})} f(\gamma;\mathbf{k})\exp(i[\mathbf{k},x]d\mathbf{k})$$

where $f(\gamma;\mathbf{k}) = \exp(-\gamma^2|\mathbf{k}|^2)$ and G is the Green function; the regularization parameter γ is found by trial and error so that inverted R_{ip}'s give the best agreement with the true optical depth field.

The performance of the IPA and NIPA was evaluated by considering the statistic

$$\frac{\sum_{j=1}^{M}|\Delta\tau_j|}{M} \qquad \overline{\Delta\tau}=\frac{\sum_{i=1}^{N_{aver}}(\tau_{orig}-\tau_{app})}{N_{aver}}$$

where $M = N/N_{aver}$, ($N = 1024$, N_{aver} = averaging scale).

For IPA $\tau_{app} = \tau_{ipa}$ and NIPA ($\tau_{app} = \tau_{nipa}$). The same statistic is also considered when assessing the impact on radiation of IPA and NIPA retrieved τ's; these radiation fields are calculated by feeding the two τ fields back to MC. The above procedure was applied on MC radiances for a one-dimensional (1-D) τ field generated by a fractal-bounded cascade cloud model, and MC albedos for a τ field that was generated from MWR data at the SGP site.

Figure 3 shows that for this bounded cascade with its moderate variability, and high sun conditions, NIPA provides only improvement to the statistics of *t* (slight for SZA = 30°, somewhat more significant for SZA = 0°), but the nadir reflectances generated from the NIPA τ's are hardly different from their counterparts using IPA τ's.

Figure 4a shows the 256-point series of MWR measured LWP converted to a 1024-point optical depth series (Figure 4b) by a) applying a two-step bounded cascade on each point, and b) assuming $r_e = 6$ μm. Cloud top variability was also added using a fractal Brownian motion model. Figure 5 shows that while NIPA has considerably improved optical depth retrievals, the improvement has little or no impact on albedo fields. From the above two examples one can see the need for studying more cases of "observed" or

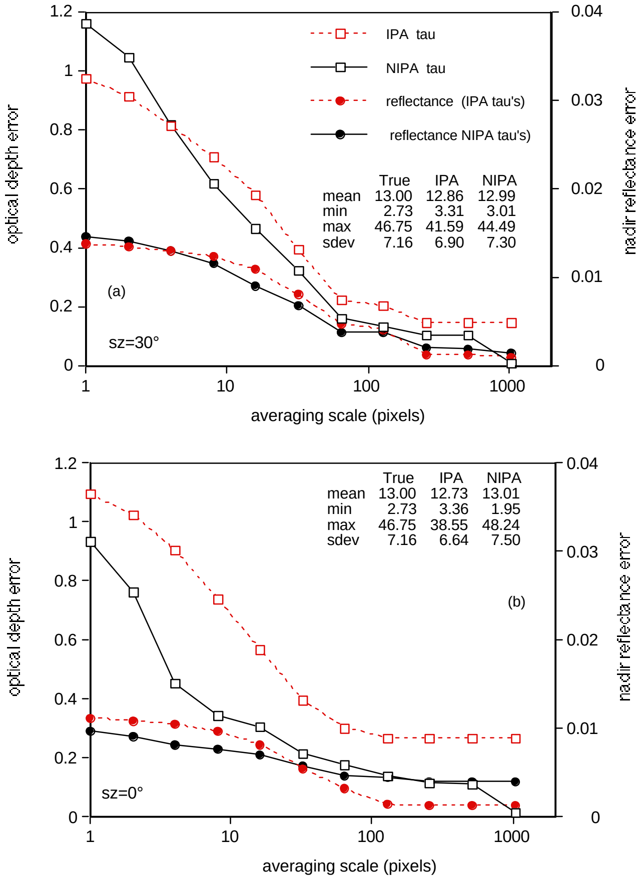

Figure 3. MC simulations; root mean square (rms) nadir reflectance and retrieved τ errors for IPA and NIPA. Parameters of NIPA: for SZA=30° (top) α=0.60, η=0.09, γ=0.0045; for SZA=0° (bottom) α=0.66, η=0.13, γ=0.0025. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/oreopoulos-98.pdf*.)

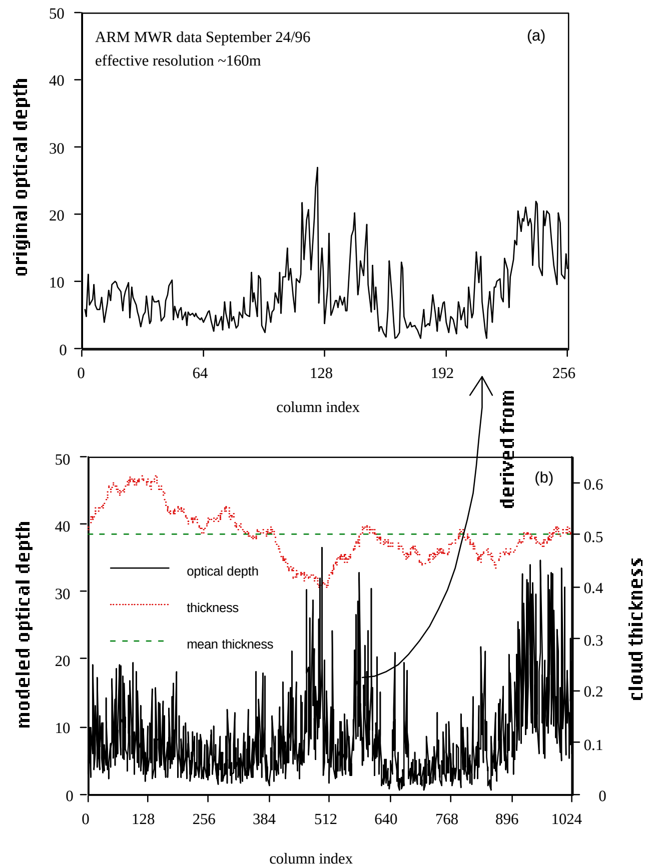

Figure 4. ARM optical depth series derived from MWR (top). Enhanced version with bounded cascade (bottom).

bounded cascade cloud fields with different characteristics (variability, pixel size, geometrical thickness), in order to correlate improvement in τ statistics with improvement in radiation fields. Whether we have used the optimal method for determining the parameters of the Green function is also a question we need to further investigate.

Discussion

The main objectives of our project are 1) to improve cloud optical property retrievals over IPA methods and transfer our knowledge to instruments with coarser resolution than TM; and 2) to use the cloud-scaling properties inferred upon accomplishing objective 1 to build more realistic cloud models. MC simulations on cloud fields produced by phenomenological and dynamical (so called "cloud resolving") models are used as a testbed for developing the improved algorithms. A fundamental unresolved issue is how to evaluate the performance of the new algorithms when applied on Landsat data. Landsat scenes over ARM sites seem to be the most appropriate for validation studies because of the presence of ground and/or airborne radiometric observations of clouds. Further research is needed to resolve practical aspects of the validation due to the breadth of spectral and spatial resolutions of the instruments and the difficulties in collocating their measurements. Additional modeling work is needed in order to extend NIPA to higher SZAs and begin tackling not only smoothing but also roughening removal. It is also important to understand under which conditions cloud retrieval improvement becomes significant enough to affect solar energetics.

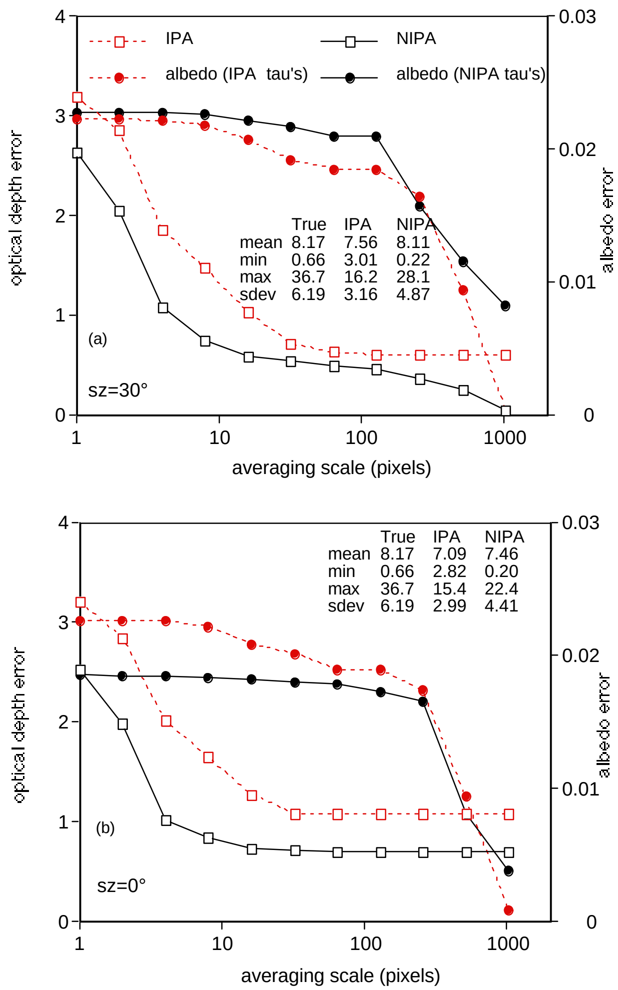

Figure 5. Retrieved optical depth rms errors of IPA and NIPA for bottom field of Figure 4 NIPA parameters: for SZA=30° (top) α=1.25, η=0.28, γ=0.0005; for SZA=0° (bottom) α=1.14, η=0.34, γ=0.0005. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/oreopoulos-98.pdf*.)

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