Retrieving Broken-Cloud Optical Thickness Using Cloud-Vegetation Interaction and a Two-Channel Narrow Field of View Radiometer

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Introduction

We study the removal of the ambiguity in measured downwelling radiances in the simultaneous presence of broken clouds and green vegetation. This ambiguity normally makes remote sensing of cloud properties difficult or impossible. The key to solving this problem is the very different spectral behavior of cloud liquid water drops and green vegetation (Figures 1a and 1b). For example, cloud optical properties, and hence cloud reflectivities, change little between 0.65 μm and 0.86 μm, while the vegetated surface albedo, ρ_{sur} changes from 0.1 to 0.5 (Tucker 1979) between the same two wavelengths. This spectral contrast in surface albedo suggests using ground measurements at both wavelengths not independently, but as an algebraic combination (a spectral index).

Based on this idea, we have developed a new technique to retrieve cloud optical depth for broken clouds above 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. Above 0.7 μm, the green vegetation acts as a powerful reflector that "illuminates" horizontally inhomogeneous clouds from below. This provides the extra information needed to largely remove the radiative effects of the three-dimensional (3-D) cloud structure, especially in the case of broken clouds; this in turn allows the retrieval of cloud optical depth using traditional one-dimensional (1-D) radiative transfer theory.

Other investigators have retrieved cloud optical depth from upward-looking measurements using 1-D radiative transfer algorithms (Min and Harrison 1996; Leontieva and Stamnes 1996). But these retrievals give credible results only for completely overcast sky and/or substantial averaging (e.g., Ricchiazzi et al. 1995). In the case of broken clouds, any inversion technique based solely on 1-D radiative transfer will almost surely fail.

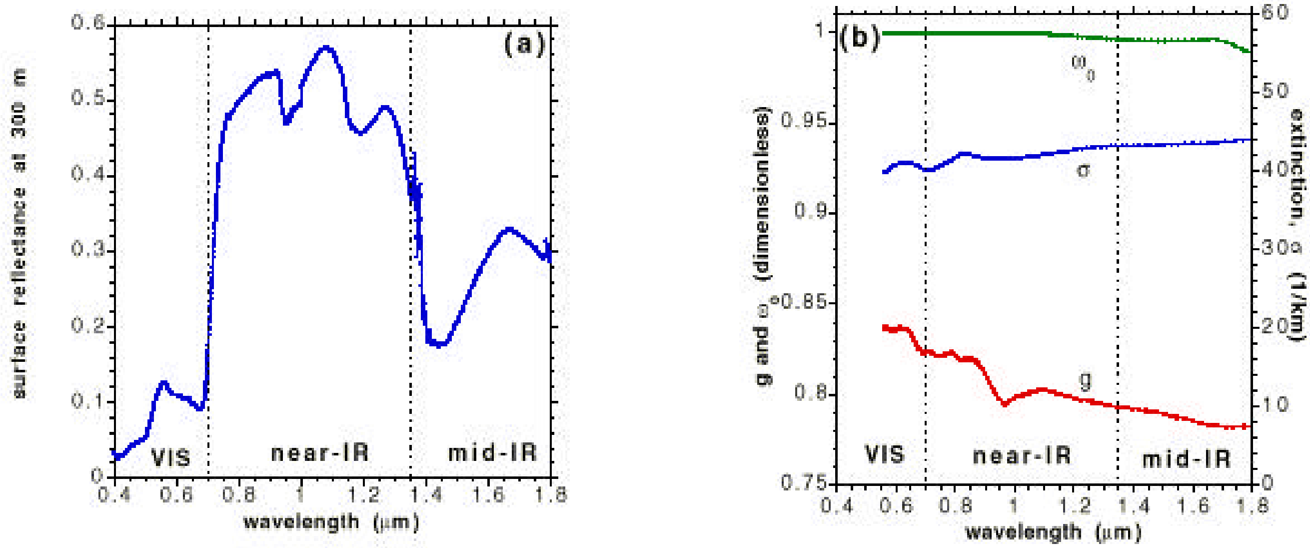

Figure 1. Spectral properties of vegetation and clouds. (a) Surface reflectance was measured in Israel from an airplane at 300 m in May 1998 (Andrew Wald, private communication). (b) Cloud optical properties: single-scattering albedos, ϖ_0, phase function asymmetry parameter, g, and extinction coefficient, σ. Data correspond to CS (small-drop) clouds used in the Intercomparison of Radiative Codes in Climate Models.

Approach

3-D Radiation Effects of Broken Clouds

For a simulated broken cloud field whose optical depths are shown in Figure 2b, Figure 2a shows a 1000-s time series of calculated zenith radiances as "measured" by an upward-looking radiometer with 5-s averaging. Assuming a 5 m/s wind speed and frozen turbulence, this can also be interpreted as a 5-km fragment of zenith radiance measured with 25-m resolution (thus the horizontal axis units in km).

In Figure 2a, we see sharp changes in brightness around cloud edges (11.2 km) and shadows behind them (11.4 km). By contrast, in regions of large optical thickness (8 km to 8.8 km and 12.2 km to 13 km), we observe much smoother behavior of zenith radiances compared to the corresponding cloud optical depth field. This is "radiative smoothing" (Marshak et al. 1995)—a process that is determined by multiple scattering and photon horizontal transport (for experimental study, see Savigny et al. 1999). Thus, there are two competing radiative processes: shadowing (or "roughening") and smoothing. Shadowing enhances fluctuations, while radiative smoothing suppresses them. All these 3-D effects prevent a one-to-one relationship between optical depth and zenith radiances and thus make it impossible to retrieve cloud optical thickness on a pixel-to-pixel basis.

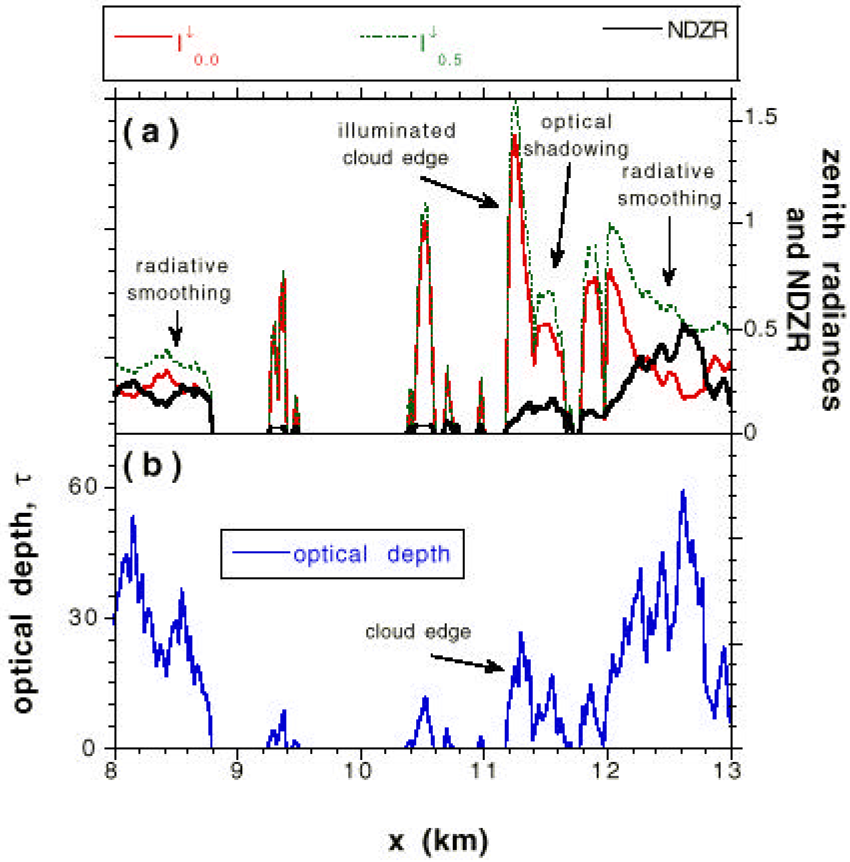

Figure 2. 3-D radiative effects. (a) A 5-km fragment of zenith radiances, $I^{\downarrow}(x)$, calculated by Monte Carlo methods for "black" surface (ρ_{sur} = 0.0), and "bright" surface (ρ_{sur} = 0.5). Spectral index normalized difference zenith radiances (NDZR) is also shown. Pixel size is 25 m, solar zenith angle θ_0 = 60° (illumination from the left), $\varpi 0$ = 1.0, Henyey-Greenstein scattering phase function. (b) A 5 km fragment of horizontal optical thickness, $\tau(x)$, that corresponds to the zenith radiances plotted in (a). 10-steps bounded cascade model (Cahalan 1994) with parameters $\langle\tau\rangle$ = 13, β = 1.4 and p = 0.35 has been used. Geometrical cloud thickness is 300 m.

Figure 3 shows power spectra of cloud optical depth and measured zenith radiances. While the power spectrum E(k) of optical depth τ is a power law with a spectral exponent $\beta \approx 1.4$ (as observed),

$$E(k) \sim k^{-\beta} \tag{1}$$

the spectrum of zenith radiances has a much more complex structure due to the dependence of the above-mentioned 3-D radiative effects on scale. For large and intermediate scales (≈ 0.5 km to 20 km) the radiance spectrum flattens, indicating larger fluctuations; for small scales the spectrum steepens, indicating smaller fluctuations. The former is a signature of shadowing, the latter of radiative smoothing.

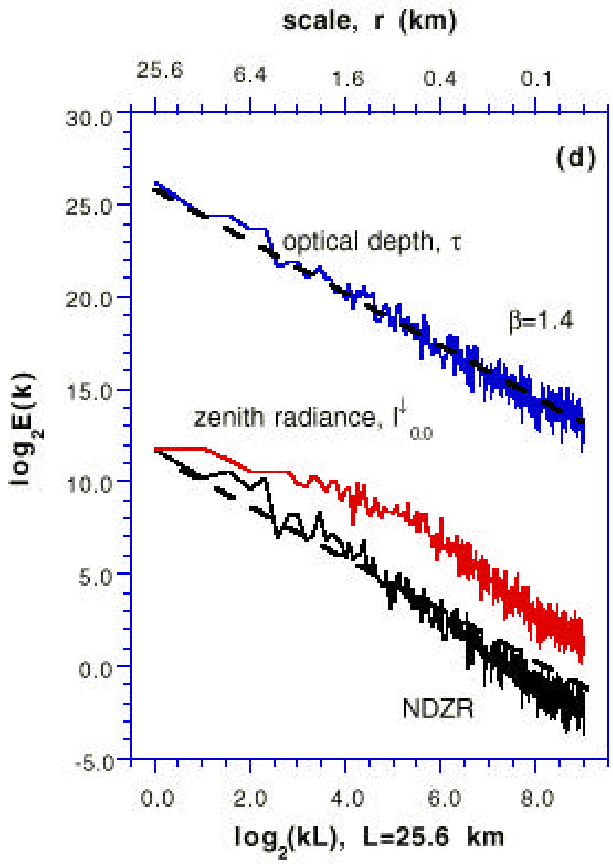

Figure 3. Power spectra of 10 realizations of cloud optical depths, zenith radiances, and NDZR. A slope $\beta = 1.4$ corresponding to the spectral exponent of a cloud optical depth model is added for convenience.

In order to use zenith radiances for estimating cloud optical properties, one has to remove the effects of shadowing and smoothing. As long as the fluctuations of cloud optical thickness and zenith radiance are qualitatively different at a given scale, it is impossible to reliably retrieve optical thickness at this scale—it becomes an indeterminate or multi-valued problem. One solution is to devise a nonlinear transformation of the radiance field that leads to power spectra similar to those of the optical depth field.

Proposed Nonlinear Transformation

The chlorophyll in green vegetation strongly absorbs solar radiation in the visible region but not in the near-infrared (NIR) region past 0.7 µm. Thus, the NIR albedo of vegetation often exceeds 50%. Vegetation (or spectral) indices that exploit this albedo contrast are quite popular. Amongst more than a dozen which have been proposed (Verstraete and Pinty 1996), the most widely used is the Normalized Difference Vegetation Index (NDVI, Tucker 1979) which is just the difference of the AVHRR NIR and red channels divided by their sum.

By analogy with NDVI, we define the NDZR as a ratio between the difference and the sum of two zenith radiances measured for two narrow spectral bands around wavelengths λ_1 and λ_2,

$$\mathrm{NDZR} = \frac{I^{\downarrow}(\lambda_2) - I^{\downarrow}(\lambda_1)}{I^{\downarrow}(\lambda_2) + I^{\downarrow}(\lambda_1)} \tag{2}$$

The wavelengths λ_1 and λ_2 are chosen to have similar cloud optical parameters but very different surface reflectance, e.g., $\lambda_1 = 0.65$ μm and $\lambda_2 = 0.86$ μm (cf. Figures 1a and b). (Note that here "I" refers not to an actual intensity but an intensity normalized by the amount of solar flux hitting the top of the atmosphere in the corresponding spectral interval.)

An Example

Figure 2a shows NDZR, along with the two zenith radiances going into its definition, for the 5-km case discussed above. We can see how the NDZR transformation largely removes 3-D effects and causes NDZR to fluctuate similarly to the cloud optical depth. NDZR is much more sensitive to cloud optical depth structure than either of the two zenith radiances, and furthermore it shows a monotonicity with respect to cloud optical depth, which augurs well for a one-to-one relationship. In the simulation, the only difference between simulated zenith radiances at wavelengths λ_1 and λ_2 is the surface albedo (spatially homogeneous, Lambertian), which was set to 0.0 and 0.5, respectively. For simplicity, all other optical and geometrical parameters of the model are the same.

The improvement is confirmed by the NDZR power spectrum (Figure 3). It has the same slope as its cloud optical depth (τ) counterpart down to about $r = 0.4$ km; below this scale, NDZR(x) is smoother than $\tau(x)$, which is clearly seen if one compares the curves in Figure 2a. This means that, averaged over a 0.4 km scale, both NDZR and τ fluctuate in phase; thus cloud optical depth can be successfully retrieved at this scale.

Theoretical Basis of NDZR

Expansion of the Downward Radiation

Any ground measurements of zenith radiance can be represented as a sum of two components: the radiation calculated for a "black" surface (bs) and the remaining radiation (rest):

$$I^{\downarrow} = I^{\downarrow}_{bs} + I^{\downarrow}_{rest} \tag{3}$$

The second component, I_{rest}, accounts for additional radiation due to surface-cloud multiple reflections.

Chandrasekhar (1950, p. 273) showed that, for the case of simple plane-parallel slab geometry and a Lambertian surface with albedo ρ_{sur},

$$I^{\downarrow}_{rest} = \frac{T^{\downarrow}_{bs}\rho_{sur}}{1 - R\rho_{sur}} \quad I_s \tag{4}$$

Here, R is the spherical albedo for isotropically illuminated clouds, $T^{\downarrow}_{bs}$ is the transmittance for a black surface, and I_s is the radiance generated by an isotropic source located at the surface.

In a 3-D case, the surface-cloud interaction term cannot be expressed in such a simple form, but the simple form (Eq. [3]) captures the essential physics—namely, that the downwelling radiance at the surface can be expressed in terms of

- the radiation in a cloudy layer for a black surface
- surface reflectance (which is independent of cloud)
- the radiation in a cloudy layer generated by isotropic sources located at the surface.

Surface-Cloud Interactions

Figure 4 is a cartoon illustrating these ideas. Using adjoint radiative transfer (e.g., Bell and Glasstone 1970), it can be shown that the surface-cloud interaction term I_{rest} can be expressed as a product of ρ_{sur} and an integral (over the whole surface) of the downward flux T and a radiative-transfer Green function G. The Green function is the cloud radiative response to the illumination from below by point sources uniformly distributed over the whole surface.

This is similar to Davis et al.'s (1997) idea of illuminating clouds by a laser beam and measuring the resulting "spot-size," which is another kind of radiative transfer Green function. Based on a diffusion approximation, Davis et al. were able to analytically derive a relationship between the spot's root mean square (rms) size and cloud optical and geometrical thicknesses.

NDZR

Since vegetation reflectance varies considerably between visible (VIS) and NIR while cloud optical properties are nearly constant, the difference between two zenith radiances $I^{\downarrow}(\lambda_1)$, $\lambda_1 \in$ VIS, and $I^{\downarrow}(\lambda_2)$, $\lambda_2 \in$ NIR, measured at the same location is equal to the difference between surface-cloud interactions at the same wavelengths.

$$I^{\downarrow}(\lambda_2) - I^{\downarrow}(\lambda_1) = I^{\downarrow}{}_{rest}(\lambda_2) - I^{\downarrow}{}_{rest}(\lambda_1) \tag{5}$$

Normalizing Eq. (5) by the sum of two radiances, we get the NDZR defined in Eq. (2). If the downward flux *T* is available, it is preferable to use it for normalization (see Eq. [4] for a 1-D case). This would lead to another NDZR, which might better describe the surface-cloud interaction.

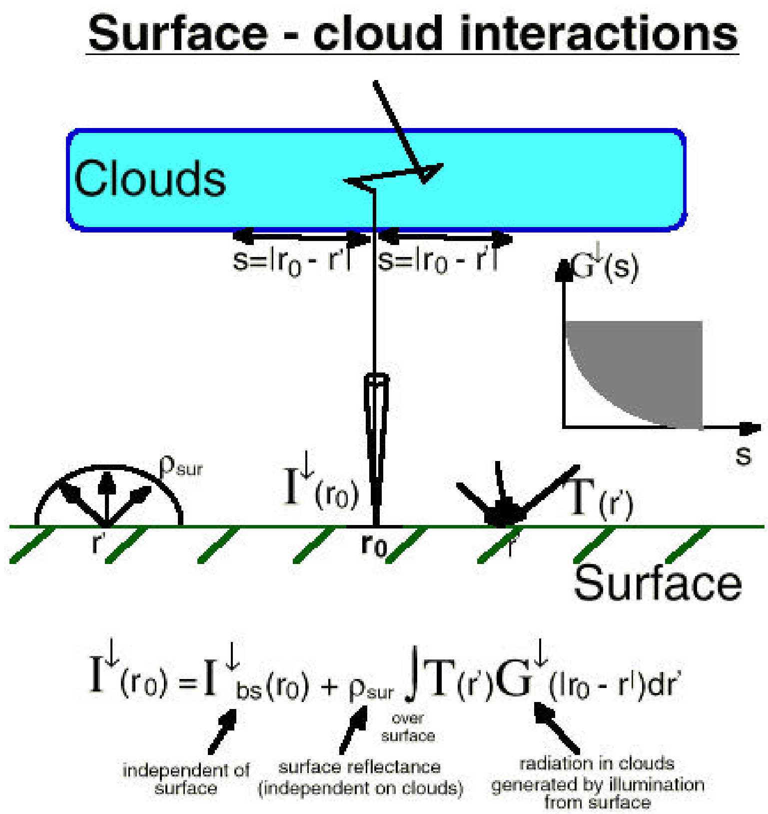

Figure 4. Surface-cloud interactions. $I^{\downarrow}(r_0)$ is measured zenith radiance at a point r_0 ; $I^{\downarrow}_{bs}(r_0)$ is zenith radiance at a point r_0 for a black surface; ρ_{sur} is surface albedo; T(r') is downward flux "measured" at r'; and $G^{\downarrow}(s)$, $s=|r_0 - r'|$, is the radiative transfer Green function = cloud response to illumination by a δ-function source at r'.

An operational instrument measuring zenith radiance (Narrow Field Of View [NFOV] in ARM-speak) has recently been installed at the Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) site in Oklahoma. With 1 sec. temporal resolution, NFOV uses a single 0.87-µm wavelength chosen to largely escape the influence of Rayleigh scattering. Adding a second channel at 0.65 µm would allow retrievals of the type indicated here.

In summary, the NDZR method uses the surface as a powerful reflector to obtain information on cloud optical properties even in the presence of strong 3-D cloud structure.

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