Reflectance vs. Transmittance Analysis of Simulated ARM Enhanced Shortwave Experiment Two-Aircraft Measurements of Fractal Clouds

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Recent analyses of solar radiation measurements below and above clouds suggest that clouds may absorb much more solar shortwave radiation than predicted by standard radiation models (Cess et al. 1995; Pilewski and Valero, 1995). To test this hypothesis, the ARM Enhanced Shortwave Experiment (ARESE) measured shortwave fluxes from aircraft at different altitudes and at multiple sites on the surface, all within the ARM Southern Great Plains (SGP) site in Oklahoma.

One way to analyze such measurements, popularized by Cess, is to plot the above-cloud-reflectance (R) as a function of below-cloud-transmittance (T). The slope $\beta = \langle dR/dT \rangle$ of the R vs. T plot, fit by a least-squares straight line, supposedly characterizes the amount of radiation absorbed by clouds. We were concerned that this approach, while working well for idealized horizontally homogeneous clouds, might lead to biases in the case of real and therefore horizontally inhomogeneous clouds. Using a realistic fractal model of marine stratocumulus inhomogeneity (Cahalan et al. 1994, Marshak et al. 1994) with gaps added in a somewhat empirical fashion, we simulated the two-aircraft measurement situation in order to study the effect of 1) various degrees of spatial averaging of upward and downward fluxes and 2) horizontal and vertical offsets between aircraft. As our “radiation instruments”, we use both 3-D Monte Carlo (MC) and independent pixel approximation (IPA) models. (The IPA is just standard plane-parallel radiative transfer theory on a pixel-by-pixel basis; as such, it ignores net horizontal fluxes.)

Comparative scale-by-scale analyses (Davis et al. 1994) of the radiation fields computed by both the MC and IPA methods shows that there is a characteristic scale η which we have dubbed the “radiative smoothing scale” (Marshak et al. 1995; Davis et al. [Accepted]). Figure 1 provides a schematic illustration of the analyses which led to this discovery. For scales larger than η, both IPA and MC radiation fields have the same statistical properties, while for scales smaller than η, the MC radiation field has a much smoother behavior, in agreement with 30-m-resolution Landsat observations. Thus, η separates two distinct scaling regimes in the radiation reflected from clouds: scales > η with a structure statistically similar to that of cloud liquid water, and scales < η where the radiation field is much smoother than that predicted by IPA.

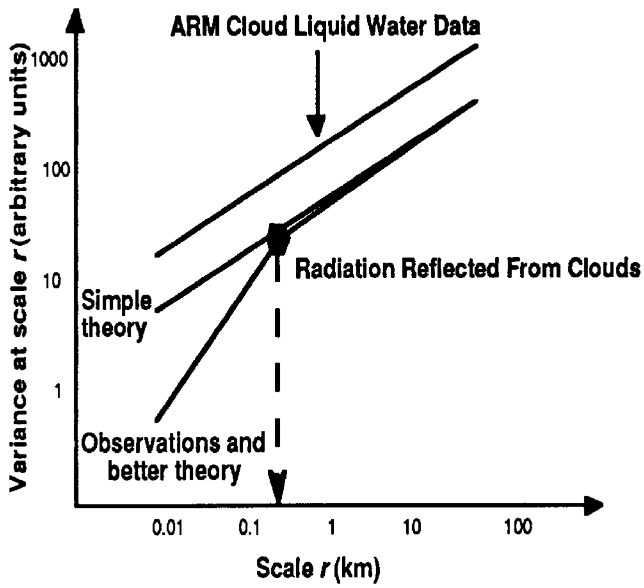

Figure 1. Log-log plot of the variance at a given scale, vs. that scale (similar to the power spectrum or a 2nd order structure function). It shows (scale-invariant) ARM cloud liquid water path data plus two computed radiation fields, IPA (“simple theory”) and MC (“better theory”). The MC curve, showing a scale break at the “radiative smoothing scale” $\eta \approx$ 200-300 m for marine Sc, agrees with Landsat observations. The IPA curve depends entirely on vertical liquid water path and thus is slaved to it, showing no scale break.

Using diffusion theory, Davis et al. (Accepted) showed that

$$\eta \approx h / [\langle\tau\rangle\ (1-g)]^{1/2} \qquad (1)$$

where values typical of marine Sc are $h \approx 300$ m and $\langle\tau\rangle \approx 13$ (the cloud's geometrical and mean optical thickness, respectively), and $g = 0.85$ is the phase function asymmetry factor. These values give $\eta \approx 215$ m.

To study the effect of horizontal fluxes and radiative smoothing on cloud absorption, we simulated Hayasaka et al.'s (1995) two-aircraft experiment over the North Pacific Ocean using our fractal bounded cascade model. Gaps were added in an empirical way by computing bounded cascade optical depths for $(\tau) = 23$, subtracting 10 from all optical depths, and rectifying. Thus, we have attempted to account both for inner cloud variability and broken cloudiness. Figure 2 shows some example results. Each point in Figure 2 corresponds to the least-squares slope (β) of the straight line fitting the scatterplot of upper-aircraft reflectance vs. lower-aircraft transmittance, where both quantities are spatially averaged over scale r. The horizontal lines correspond to IPA results, which do not depend on spatial averaging. The other curves contain MC results: the two upper curves refer to a single absorbing wavelength in the near-infrared spectral region, while the lower curve corresponds to a generic nonabsorbing visible wavelength. Note that the cloud thickness h for the two upper (near-infrared) curves is 3 times larger than for the lower (visible) curve, so their radiative smoothing scale η is also three times larger according to Eq. (1). All curves clearly show three distinct scale ranges: small scales ($r < \eta$) where β is very stable (and wrong); a transition range ($11 < r < \eta$) where β is falling rapidly; and the large scales ($r > 10\ \eta$) where MC and IPA results agree reasonably well, and β is stable and correctly characterizes cloud absorption ($\beta = 1$ for visible and $\beta = 0.76$ for near-infrared). The choice of $10\ \eta$ is actually a lower bound, typical of nonabsorbing wavelengths, and one must go to $20\ \eta$ or $30\ \eta$ to reach the large-scale regime at absorbing wavelengths.

The clear message is the R vs. T method produces a large and systematic bias (in the direction of enhanced absorption) at scales $< 10\eta$. This bias is never random. Only by averaging over scales of at least 10η is this bias mostly eliminated. The necessity for spatial averaging was understood by Pilewski and Valero, who averaged over 30-km flight segments, but our work puts such averaging on a firmer theoretical footing and shows how the necessary averaging scale varies with cloud absorption and other factors.

The only difference between the two near-infrared (upper) curves in Figure 2 is the aircraft altitudes. The middle curve

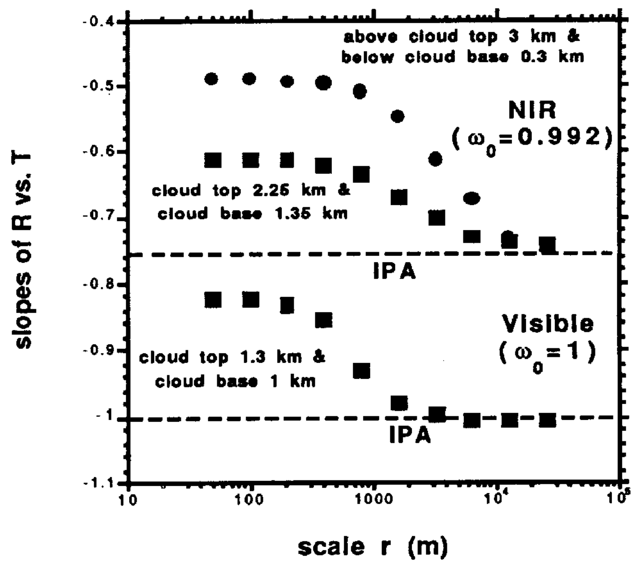

Figure 2. Slopes of above-cloud reflectance (R) vs. below-cloud transmittance (T) scatter-plot for both visible and near-infrared spectral regions, plotted against different scales of spatial averaging. Solar zenith angle 50°. Cloud thickness h = 900 m for two upper curves (1.772 µm near-infrared cases with single scattering albedo $\omega_o = 0.992$) and h = 300 m for the lower curve (visible nonabsorbing case). Mean optical thickness $\langle\tau\rangle = 13$ for all curves; asymmetry factor g=0.85. For near-infrared case, absorption is by liquid water droplets only. The simulated cloud occupied the 1-1.3 km vertical layer for the lower (visible) curve, for which the simulated aircraft flew exactly at cloud top and base. It occupied the 1.35-2.25 km vertical layer for the upper (near-infrared) curves: for the lower of these, the simulated aircraft flew exactly at cloud top and base again; for the upper, at 0.3 and 3 km corresponding roughly to the Hayasaka et al. aircraft positions.

is for measurements taken exactly at cloud top and bottom, while the upper curve is for aircraft 750 m above cloud top and 1005 m below cloud bottom (22 January flight described in Hayasaka et al. 1995). Comparing these two curves, we see that the bias in slope β for averaging scales $< 10\eta$ actually increases with the vertical distance between aircraft and cloud. This result is somewhat counterintuitive, since both upward and downward fluxes should be increasingly smoothed the farther one is from the cloud (Barker, 1995). However, in the case of broken clouds, sharp peaks in the downward flux near cloud gaps (see Figure 3 and Hayasaka et al. 1995) are not smoothed. Hence, while the pixel-to-pixel variance of reflectivity decreases with distance from cloud top, the variance of transmission remains nearly the same; as a result,

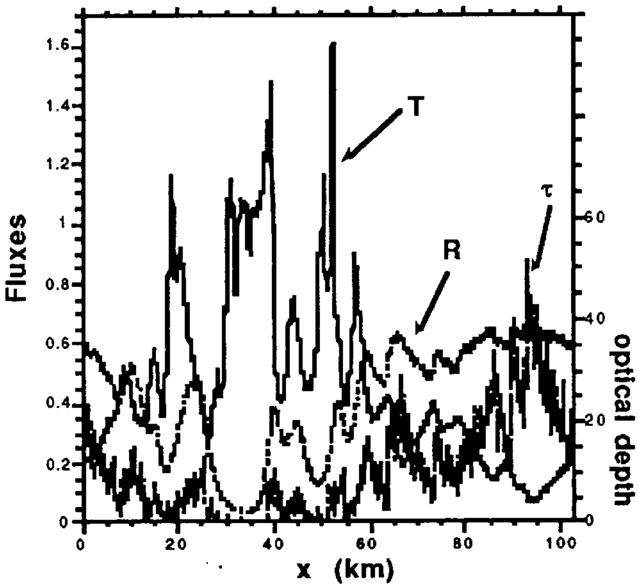

Figure 3. Horizontal variations of optical depth (τ), reflectivity (R), and transmission (T) at the near-infrared wavelength. R is measured at 3 km (cloud top is at 2.25 km) while T is measured at 0.3 km (cloud bottom is at 1.35 km). Other parameters are the same as for upper curve in Figure 2.

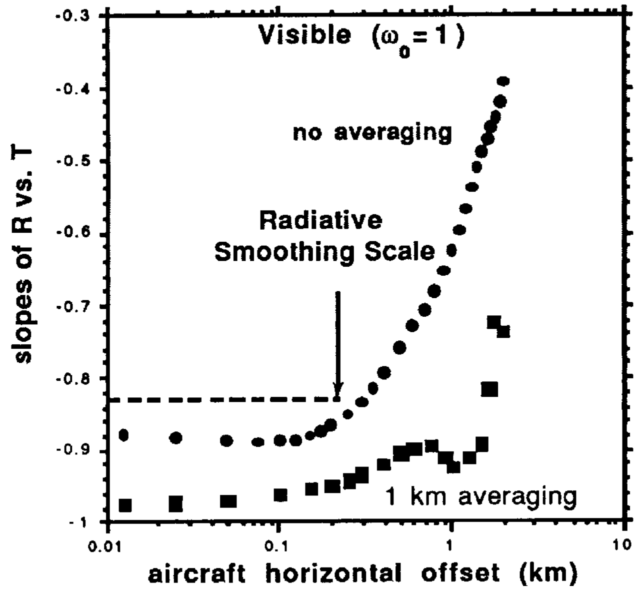

Figure 4. Slope β of reflectivity (R) vs. transmission (T) plotted against the horizontal offset between above- and below-cloud aircraft (flying exactly at cloud top and base). Nonabsorbing case for which slope should be -1. One curve corresponds to spatial averaging of fluxes over 1 km, the other to no spatial averaging. Scene is completely cloudy; sun angle 22.5°, g = 0.85 and <τ> = 13. Horizontal variability of cloud optical depth is scale invariant with H = 1/3, Eq. (1).

the magnitude of β decreases and to estimatecloud absorption correctly, more rather than less spatial averaging is required.

Another source of bias in estimating cloud absorption is the horizontal offset between two aircraft flying above and below clouds. Assuming scale invariance in the horizontal distribution of optical depth,

$$\langle|\tau(x+s) - \tau(x)|\rangle \sim s^H \quad (0<H<1) \tag{2}$$

one can show that even in the case of IPA with conservative scattering

$$|1 - \beta| \sim s^H \tag{3}$$

In the limit of uncorrelated optical depth (H = 0), β = 0, and any offset between aircraft is disastrous for estimating absorption. For H > 0, β deviates increasingly from (the correct value of) unity as either horizontal offset S or exponent H increases. Note that H= 1/3 best fits the horizontal variability of cloud liquid water as defined by Eq. (2) (Cahalan et al. 1994, Davis et al. 1994).

Figure 4 illustrates this point for a MC experiment in a completely cloudy scene in the visible region. There is a plateau in β up to the radiative smoothing scale η: because of net horizontal fluxes, aircraft offsets smaller than η have little effect on β. This plateau gives a wrong value of β unless fluxes are spatially averaged. For scales larger than η, we are increasingly in the IPA regime and Eq. (3) begins to describe the general functional behavior of the rising portion of the curves. As horizontal offset increases, η drifts systematically away from its true value, falsely indicating absorption, although this drift is mitigated by spatial averaging of fluxes.

To conclude, horizontal fluxes are a major source of systematic bias in cloud absorption estimates based on two aircraft and the R vs. T method. The bias is always in the direction of “enhanced absorption.” It can always be eliminated by sufficient spatial averaging if the aircraft are perfectly (within a few hundred meters) stacked. The characteristic cloud radiative smoothing scale η determines how much spatial averaging is necessary. Averaging measurements over scales r smaller than η give a slope β = <dR/dT> much smaller in magnitude than the one estimated by plane-parallel models. For broken clouds, β is very sensitive to how far below and above clouds we measure upward and downward fluxes; it actually moves away from the correct value as the upper aircraft increases its altitude above cloud top. As a result, more spatial averaging must be performed to reach the IPA regime, and, therefore, accurate estimates of cloud absorption. Horizontal offsets between two aircraft, if not properly accounted for, also contribute to a decrease of $|\beta|$ which could be mistaken for enhanced absorption.

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