Spectral Cloud Emissivities from LBLRTM/AERI QME

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Introduction

Using spectral radiance measurements from the atmospheric emitted radiance interferometer (AERI) and calculations from the Line-by-Line Radiative Transfer Model (LBLRTM), cloud emissivities can be derived in the window region from 700 cm^{-1} to 1250 cm^{-1}. The AERI/LBLRTM Quality Measurement Experiment (QME) (Brown 1998) is currently designed to run under clear-sky conditions; the LBLRTM does not calculate the effects of cloud optical properties on the measured spectral radiance at the surface. Therefore, in the presence of a cloud, the difference between the AERI measurements and the LBLRTM calculations are primarily due to that cloud's optical properties, within the normal level of agreement between the model and instrument. Using conservation equations and some approximations, we can derive a semi-empirical estimate of cloud emissivities, which could eventually help parameterize cloud property models in GCMs.

Cloud Model

For our initial analysis, we chose a very simple cloud model. The Atmospheric Radiation Measurement (ARM) micropulse lidar (MPL) determines the presence of a cloud and the corresponding cloud base height (CBH). We then assume a single infinitely thin, plane-parallel cloud layer that radiates as a "gray body":

$$R_{cloud} = \varepsilon B_c(\theta) \qquad (1)$$

where ε is the cloud emissivity and $B_c(\theta)$ is the blackbody radiance at cloud temperature θ.

Equations of State

To derive the cloud emissivity, we divide the atmosphere into regions above and below the cloud, and calculate the radiance contribution at the surface from each section:

$$R_{AERI} = R_d + \varepsilon B_c(\theta)T + tR_a T + rR_u T \qquad (2)$$

where R_{AERI} is the observed radiance at the surface, R_d is the downwelling radiance from below the cloud to the surface, R_a is the downwelling radiance from above the cloud to the cloud base height, R_u is the upwelling radiance from below the cloud to the cloud base height, T is the atmospheric transmittance from the CBH to the surface, and ε, r, and t are the emissivity, reflectivity, and transmittance of the cloud.

In words, Eq. (2) states that the observed radiance at the surface is the sum of the radiances from the atmosphere below the cloud, emitted from the cloud itself, transmitted through the cloud from above, and reflected off the cloud from below.

Of the above quantities, only R_{AERI} is directly observed. R_d, R_a, R_u, and T are all calculated from LBL model runs, while ε, t, and r are derived from this analysis.

We can get another equation of state by conserving energy at the CBH:

$$\varepsilon + t + r = 1 \qquad (3)$$

Approximations

Unfortunately, we have three unknowns (the cloud parameters ε, t, and r) and only two equations. Therefore, we need to make one of two approximations: the *thin cloud approximation*, which assumes no cloud reflectivity (r = 0); or the *opaque cloud approximation*, which assumes no transmittance through the cloud (t = 0).

The thin cloud approximation leads to the following effective emissivity:

$$\varepsilon_{thin} = \frac{R_{AERI} - R_d - R_a T}{B_c T - R_a T} \qquad (4)$$

Similarly, the opaque cloud approximation gives us:

$$\varepsilon_{opaque} = \frac{R_{AERI} - R_d - R_u T}{B_c T - R_u T} \qquad (5)$$

Theoretical Errors

We can describe the errors in these approximations analytically. If we define the error δ such that $\varepsilon_{real} \equiv \varepsilon_{approx} + \delta_{approx,}$ then thin cloud errors are given by:

$$\delta_{thin} = \frac{r(R_a T - R_u T)}{B_c T - R_a T} \qquad (6)$$

while the opaque cloud errors are given by:

$$\delta_{opaque} = \frac{t(R_u T - R_a T)}{B_c T - R_u T} \qquad (7)$$

Typically, R_u is much greater than R_a, because the thermally radiating part of the atmosphere is concentrated near the surface. This means that as long as $B_c T > R_{u,a} T$ (which is usually true), ε_{thin} will usually be larger than ε_{real}, while ε_{opaque} will be smaller than ε_{real}.

Below CBHs of 3 km, R_a starts to approach R_u, as more of the lower atmosphere goes above the cloud. This has the interesting side effect of minimizing the theoretical errors in our approximations for low clouds.

Ensemble Averages

We analyzed 1192 total cloud emissivity runs using data from the ARM Southern Great Plains (SGP) site from April 11, 1994, to January 28, 1998, whenever the regular AERI/LBL QME was run and the MPL indicated the presence of a cloud. Our first simple parameterization of these clouds divided them into four groups based on CBH: from surface to 3 km, 3 km to 6 km, 6 km to 9 km, and above 9 km. Within each CBH group, we took the ensemble means and standard deviations of our effective emissivities at each monochromatic frequency within the window region from 700 cm^{-1} to 1250 cm^{-1}. Before averaging, we clipped any monochromatic emissivity that fell outside the range $\varepsilon(\nu) \in [-0.5, 2.0]$. This gross outlier check on our final calculated value was the only quality assurance we performed on our dataset.

Analysis

For all CBH regions, the thin cloud approximation is as or more believable than the opaque approximation (Figure 1). For clouds below 3 km, $\varepsilon_{thin} \approx \varepsilon_{opaque}$ as R_a approaches R_u; for higher clouds, ε_{opaque} approaches zero (or goes negative) and is highly variable across many runs (Figure 2).

The standard deviations in ε_{thin} increase somewhat as the CBH decreases, from about .05 for CBH above 9 km to .15 for CBH below 3 km. The thin cloud approximation is probably more accurate for higher (and optically thinner) clouds; there are also fewer complications such as multiple cloud layers with high clouds. Nevertheless, the thin cloud emissivities seem adequate for exploring clouds of all heights, and we will use ε_{thin} exclusively as our effective emissivity in the rest of this analysis.

Figure 3 plots the thin cloud emissivities together. As expected, ε_{thin} decreases as cloud base height increases and the clouds become optically thinner. Figure 3 also allows us to examine the spectral content of our effective emissivities. The fine structure (peaks) are not real features of the emissivity and are probably due to errors in the modeled line strengths and shapes (note that $\varepsilon \sim R_{AERI} - R_{LBL}$). Nevertheless, there is a strong spectral content in ε_{thin}, especially for clouds above 9 km. This should have some implications for GCMs, which currently model emissivities purely as a function of cloud liquid water and ice water content, without any spectral dependence at all.

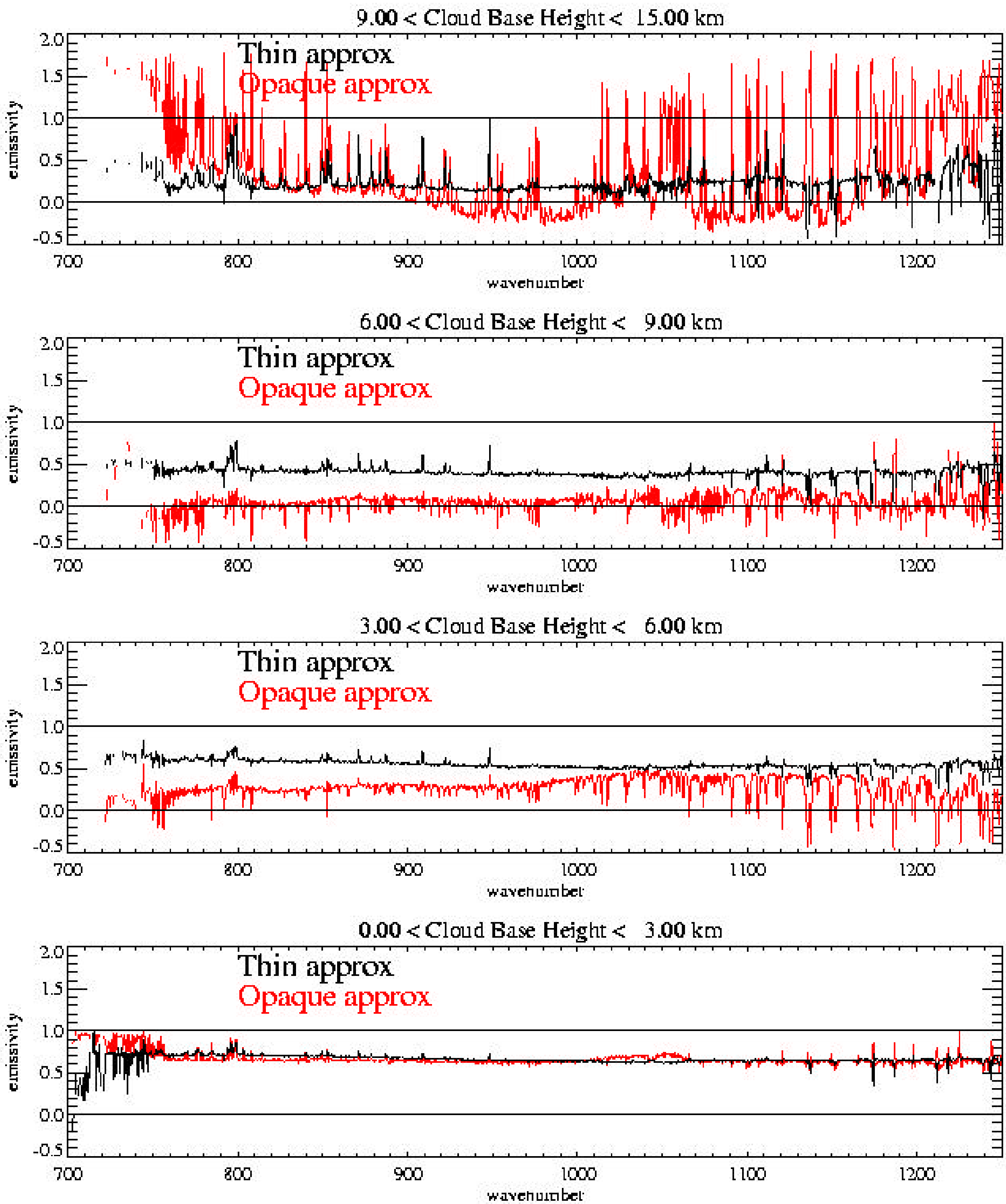

Figure 1. Ensemble averages of effective emissivities, thin and opaque cloud approximations, from 1192 runs from April 4, 1994, to January 28, 1998. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/shippert-98.pdf*.)

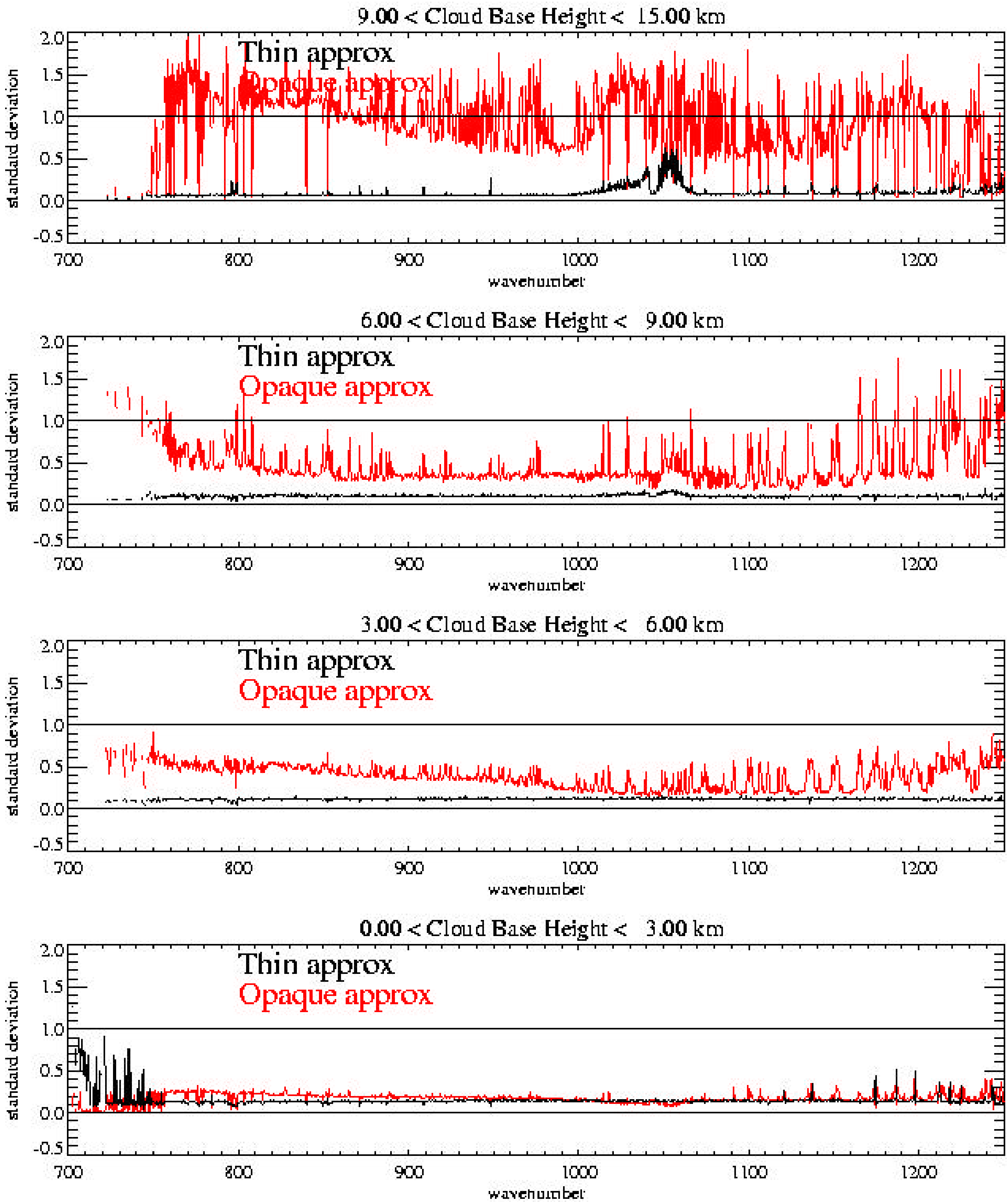

Figure 2. Standard deviations of effective emissivity ensemble averages. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/shippert-98.pdf*.)

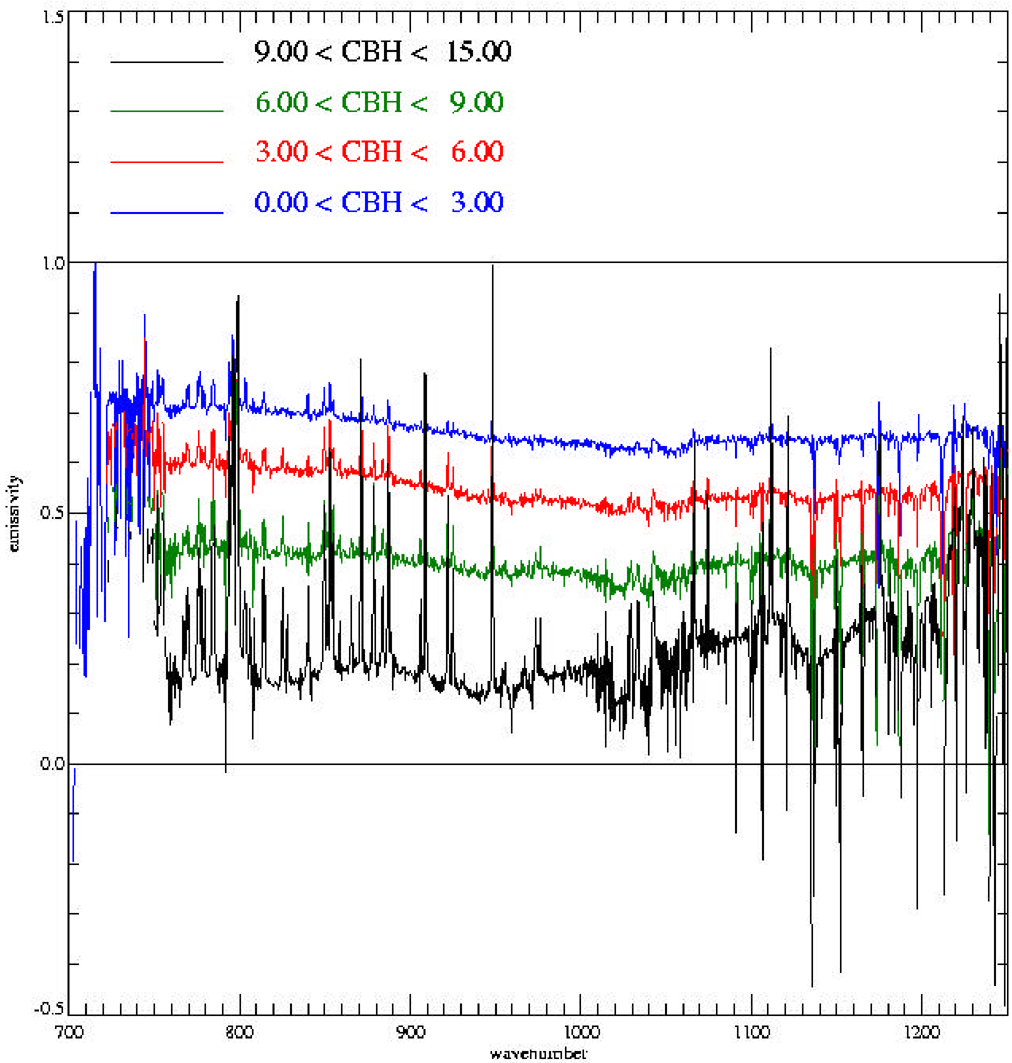

Figure 3. Thin cloud emissivity ensemble means. (This is the same data as Figure 1.) (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/shippert-98.pdf*.)

Cloud Spatial Thickness

An initial attempt was made to investigate the effect of cloud spatial thickness upon our effective emissivities. We derived spatial thickness by using cloud top minus cloud base from the MPL.

One would expect spatially thicker clouds to have higher emissivities, because of their increased water content. However, we were unable to find any significant correlation between our calculated ε_{thin} and cloud spatial thickness. The problem is in our measure of thickness, because the MPL beam attenuates in clouds with large liquid water content, thereby giving a cloud top that is too low. Furthermore, it is precisely those clouds with high liquid water content that will have high emissivities. So we end up with spatially "thin" clouds (according to the MPL) that nevertheless report high emissivities, rendering our analysis useless.

Ultimately, what we really need is a good measure of the *optical* thickness of the cloud, for which spatial thickness may or may not be a good substitute.

Future Directions

The next step in developing a useful cloud emissivity data product is to get a better description of the cloud itself. Initially, we should develop some sort of outlier detection scheme to eliminate from our ensemble averages multiple cloud layers, broken cloud fields, and other scenarios that do not match our simple plane-parallel cloud model. In the longer term, we need better measures of cloud height, optical thickness, liquid and ice water content, and any other cloud property that allows us to more accurately calculate the effective emissivity. Accurate measures of cloud parameters will also allow us to compare our semi-empirical emissivities with existing emissivity parameterizations in GCMs, and could lead to more sophisticated cloud models for use in our calculations (e.g., to model a real 3-D cloud).

Summary

By solving a system of equations consisting of the conservation of energy at the surface and at the cloud base along with one cloud property approximation, we are able to derive an effective emissivity over the region from 700 cm^{-1} to 1250 cm^{-1} using AERI observed and LBL modeled radiances. The thin cloud approximation is more stable and believable than the opaque approximation at all cloud heights, and is therefore the best measure to use for our "effective emissivity." Initial analysis indicates that ε_{thin} varies as expected with cloud height (to the extent that CBH is a measure of optical thickness) and shows significant spectral variance over the region.

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