Constraints on Excess Absorption: Computations by a Broadband Monte Carlo Model

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Introduction and Motivation

The topic of excess absorption has motivated us to scrutinize our understanding of atmospheric radiative transfer and the potential effects of uncertainties therein. Because water vapor is a primary absorber of solar radiation, our group first focused on examining the potential uncertainties in water vapor transmission models using Atmospheric Radiation Measurement (ARM) data. The results, presented at last year's ARM Science Team meeting, showed no significant discrepancies in such models in clear skies. Specifically, we showed that the uncertainties in the physics of water vapor absorption are not responsible for clear-sky excess absorption beyond measurement uncertainties (Conant et al. 1997, 1998). Further, neglecting the near-infrared, non-Lorentzian water vapor continuum contributes only < ~2 Wm^{-2} (diurnal average) to clear-sky excess absorption (Vogelmann et al. 1997, 1998).

Several studies have suggested that cloud geometry may have a significant effect on flux calculations (e.g., O'Hirok and Gautier 1997). We used narrowband Monte Carlo calculations with an absorbing atmosphere and idealized cloud shapes to understand the importance of various three-dimensional (3-D) cloud geometries and water vapor distribution on narrowband, near-infrared solar absorption. We found that significant differences can exist in absorption between plane-parallel and classic 3-D cloud geometries, and that a thin saturated water vapor layer above cloud top systematically enhances absorption (Podgorny et al. 1998).

Motivated by these results, we developed a computationally efficient broadband Monte Carlo model to examine the effects of assumptions used in standard plane-parallel radiative transfer models on absorption. The new model's flexibility and speed also will enable the use of many ARM data types, thereby providing a new means for us to pursue linking the in situ observations to regional-scale cloud-radiative fields. Our objectives here are to constrain the likely causes of excess cloud absorption by quantifying the effects of standard modeling assumptions regarding model physics and cloud geometry.

Model Features

The model is flexible and treats clouds with arbitrary shapes, liquid water distributions, 3-D distributions of saturated water vapor, and two-dimensional (2-D) variations in the ground albedo. The flexibility of the Monte Carlo code also allows treating non-standard physics. Gaseous absorption by water vapor, ozone, oxygen and carbon dioxide are incorporated using correlated-k distributions for 107 bands covering the solar spectral region from 0.29 µm to 4 µm. The model is computationally efficient; on a workstation, height-dependent, spectral atmospheric absorption may be computed on order of magnitude of 1 hour. This efficiency enables multiple sensitivity tests and ensemble statistics. Calculations have been validated with comparisons using discrete ordinate radiative transfer (DISORT) and the Spherical Harmonic Discrete Ordinate Method (SHDOM) (Trautmann et al. 1998).

Results

Model Physics Tests

We first examine the effects of simplifying assumptions implicit in standard model physics. A multiple-scattering model typically uses layer-average scattering properties that are produced from a single-scattering average of the various properties present. However, it is not clear that this approach would produce the same results as if the separate scattering properties were input into the model and the multiple scattering performed the averaging. Thus, two sets of sensitivity tests are performed to determine the following:

1. Is the multiple-scattering solution for average cloud scattering properties equivalent to that if the cloud size-bin-resolved scattering properties are used? (i.e., Is Radiative Transfer $(\beta(r), \omega(r), g(r)) \approx$ Radiative Transfer $(\overline{\beta(r)}, \overline{\varpi(r)}, \overline{g(r)})$?)

2. Is the multiple-scattering solution for average layer properties (mixture) equivalent to that when the species' scattering properties are treated separately? (i.e., Is Radiative Transfer (mixture) ≈ Radiative Transfer (Rayleigh, Aerosol, Cloud)?)

Tests for a variety of conditions found very close agreement in absorption when the single-scattering averaged values are used and when the individual properties are explicitly represented.

We also evaluated the difference in the solutions when the exact Mie phase function for a water cloud is represented using the Henyey-Greenstein phase function. We find negligible differences in absorption, but a 2% change in the reflectivity and transmissivity for a thick precipitating cloud. This result is consistent with that by Fomin and Gershanov (1997).

3-D Cloud Geometry

We determine the 3-D broadband effects of varying cloud shape, treating 3-D saturated water, and varying the cloud microphysics. The idealized cloud shapes tested are a) plane-parallel, b) wavy cloud (2-D sinusoidal top with wavelengths 1 km in the x and y directions), and c) broken cloud (the wavy cloud with holes where the sine wave is negative). The fractional cloud cover for the broken cloud field is 50%. Its absorption is compared to that for the other two cloud types for equal fractional cover, composed by weighting 50% clear sky with either the wavy or plane-parallel solution (the latter being what is used in climate models). Water vapor is saturated in the cloud layer only where cloud exists. For these studies, we define a reference case as an unsaturated ARM Enhanced Shortwave Experiment (ARESE) water vapor profile, 50% cloud cover, scene average optical depth (at 0.5 μm) of 7.5, cloud base height of 1 km, cloud thickness of 0.6 km, and cloud drop effective radius of 5 μm.

Resulting diurnal averages of radiative properties are given in Table 1 as a fraction of the top-of-atmosphere solar flux for the reference plane-parallel result, and departs from this result for some cases tested.

Table 1. Diurnally averaged effects for an ARESE case.

Property	**Plane Parallel Cloud Results**	**Difference from Plane-Parallel Result ($X\%-X\%_{PP}$)**
	Reference Case (unsaturated)	Broken Cloud and Saturated Cloud Layer
Absorptivity	18.3%	+1.2
Reflectivity	31.1%	+8.8
Transmissivity	50.5%	-9.9
	Plane-Parallel Rain Cloud (saturated, r_{eff}=68 μm)	Broken Field Rain Cloud
Absorptivity	21.1%	+2.6

Discussion

We have developed a broadband Monte Carlo model and examined the effects on absorption of some assumptions used in standard plane-parallel radiative transfer models. For the cases and configurations studied here, we find the following:

1. Assumptions in standard model physics have a negligible effect on absorption for a) cloud bin-resolved scattering properties versus averages over the size-bins, b) specie separation versus average scattering properties, and c) Mie versus Henyey-Greenstein phase function (water clouds).

2. Saturating the water vapor in the cloud layer enhances the diurnal average absorption by <1.5%, which depends on cloud shape and cloud height (not shown).

3. 3-D clouds considered in this study enhance absorption by <0.8% from the plane-parallel equivalents, which is much less than the 8% difference found for excess absorption.

4. However, broken, precipitating clouds can enhance absorption by 2.6% over the plane-parallel case.

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Other Publications in Progress

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