Deficient Model Absorption

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Recent studies have shown a discrepancy of more than 25-35 Wm^{-2} (diurnal average) between observations of the absorption of solar radiation in the atmosphere in the presence of clouds and estimates from standard radiative transfer models. The differences have been attributed to errors in measurement methodologies, unresolved problems in understanding of cloud microphysics, and the portrayal of clouds as homogeneous plane parallel entities within radiative transfer models. Using a Monte-Carlo-based radiative transfer model, we demonstrate that theoretical modeling is brought closer into agreement with observations when cloud three-dimensional (3D) effects are included.

Radiative Transfer Computations

The 3D radiative transfer computations are performed using the Monte Carlo approach. Essentially, it is a direct simulation of the physical process involved in radiative transfer, whereby the path of an individual photon is defined by a set of probability functions. These functions describe the distance a photon travels before an interaction; the result of the interaction (absorption or scattering); and if scattered, the scattering direction. The probabilities vary with the atmospheric constituents involved and the photon wavelength. The model we have developed contains all major atmospheric gases, aerosols, and cloud microphysics (see Table 1a). A comparison of broadband (0.25-4.0 μm) solar absorption, transmission, and reflectance for clear and cloudy skies calculated using the Monte Carlo model and a discrete ordinate radiative transfer model (SBDART) show discrepancies generally less than 1%.

The model was run in three modes on the cloud field described in Table 1b and shown in Figure 1. For plane parallel (PP) mode, computations are made separately for a clear and cloudy sky and results combined according to weights based on the areal extent of clouds within the field. For the independent pixel (IP) mode, flux computations are similar to the PP mode, except that calculations are made for each cloud element individually, rather than for the ensemble average. The 3D mode uses the same field as the IP mode, but allows for the horizontal diffusion of photons.

Results

When cloud morphology is accounted for in the radiative transfer calculations, atmospheric absorption is higher by 21 Wm^{-2} at a 45 solar zenith angle with an average increase of 17 Wm^{-2} during the daylight hours (Figure 2). Part of the difference between the 3D and PP results can be attributed to the averaging of nonlinear radiative effects evident by the slightly higher amount of absorption in the IP results.

The spectral difference between the 3D and IP mode shows that enhanced absorption occurs predominantly in the near infrared because of both gaseous and cloud droplet absorption (Figure 3). The amount and type of absorption is a function of solar zenith angle. At a low solar zenith angle, enhanced water vapor absorption dominates, but as the angle of the sun steepens, the enhancement due to cloud droplets becomes predominant. At a 60 solar zenith angle, the enhanced absorption actually comes at the expense of absorption by water vapor.

From the spectral evidence and an examination of the spatial profiles of absorption, two mechanisms for enhanced absorption in 3D clouds may be inferred (Figure 4). At the lower solar zenith angles, 3D clouds transmit more photons through cloud leakage to lower levels in the atmosphere where greater amounts of water vapor enhance absorption. As the solar zenith angle steepens, photons in the 3D mode are not limited to entering cloud tops as is the case for IP. Thus, the photons can penetrate deeper into the cloud, increasing the chance of being absorbed by a cloud droplet. Additionally, photons that would be reflected back out to space in the IP mode may be scattered back into adjoining clouds in the 3D case.

Table 1 (A). Description of model details.
Computations performed at 0.005-mm interval from 0.25-4.0 μm
K-fit gaseous transmission functions LOWTRAN 7
Cloud microphysics computed from Mie scattering theory
Aerosol optical properties based on LOWTRAN 7
Surface optical properties derived from 5S model
47 vertical layers from 0 to 100 km with 400-m resolution within clouds
50 x 80 horizontal cells at 800 m resolution
Monte Carlo computations performed at each wavelength until convergence of domain atmospheric absorption, transmission and reflectance to less than 0.1% taken at three 32,000 photon count intervals
(B) Description of model input
Standard tropical atmosphere, cloud relative humidity = 95%
Cloud field morphology based on cloud top heights from AVHRR images
Cloud base @ 1200 m, with maximum thickness of 8800 m (mean = 4800)
Small cumulus congestus clouds based at 1200 m with maximum 1600 m^2 extent
Scattered altostratus cloud layers 800- to 1200-m thick based at 6 km
Effective radius range 4.2 - 16 μm (mean = 11.6)
Maximum optical depth = 220 (mean = 92.4)
90% cloud coverage
Oceanic aerosols (20-km visibility)
Ocean surface

As briefly shown, part of the observed enhanced absorption is not a result of a lack of theoretical understanding, but simply the result of not addressing the error associated with the plane parallel cloud assumption. Hence the issue of “anomalous” or “enhanced” cloud absorption may be more appropriately viewed as “deficient model absorption.”

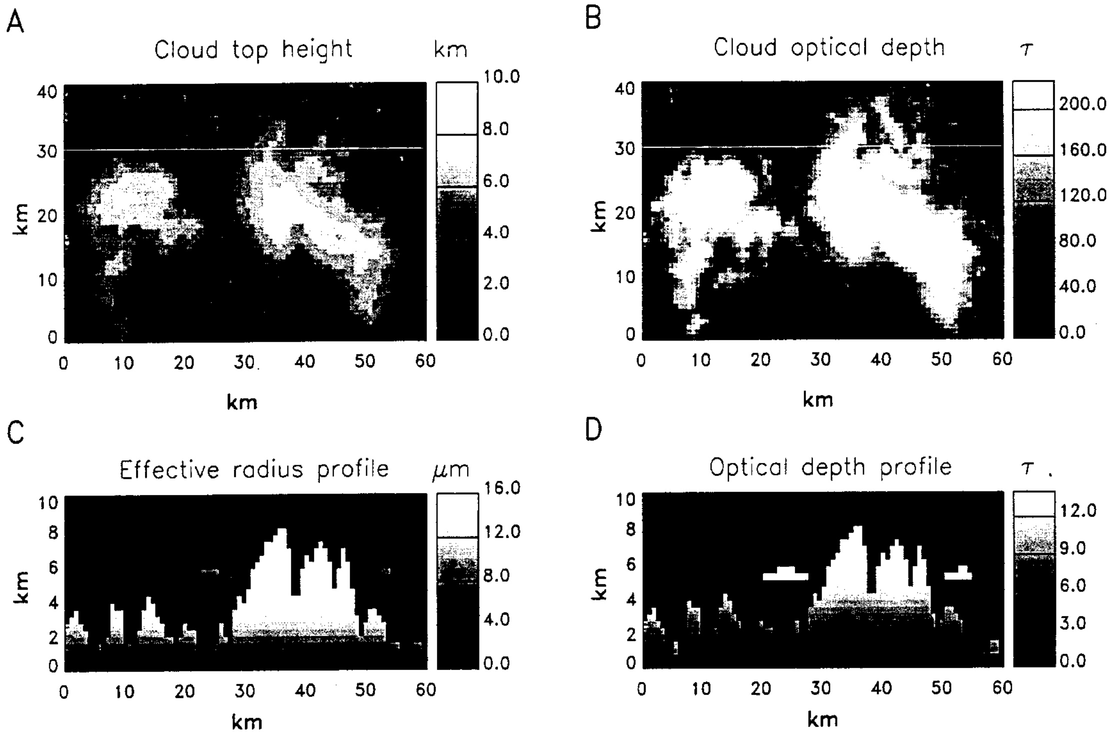

Figure 1. (A) Cloud top height (km). White line represents 30-km east-west transect. (B) Vertically integrated cloud column optical depth τ. (C) Vertical profile of effective radius at 30-km east-west transect. (D) Vertical profile of Optical depth along 30-km east-west transect.

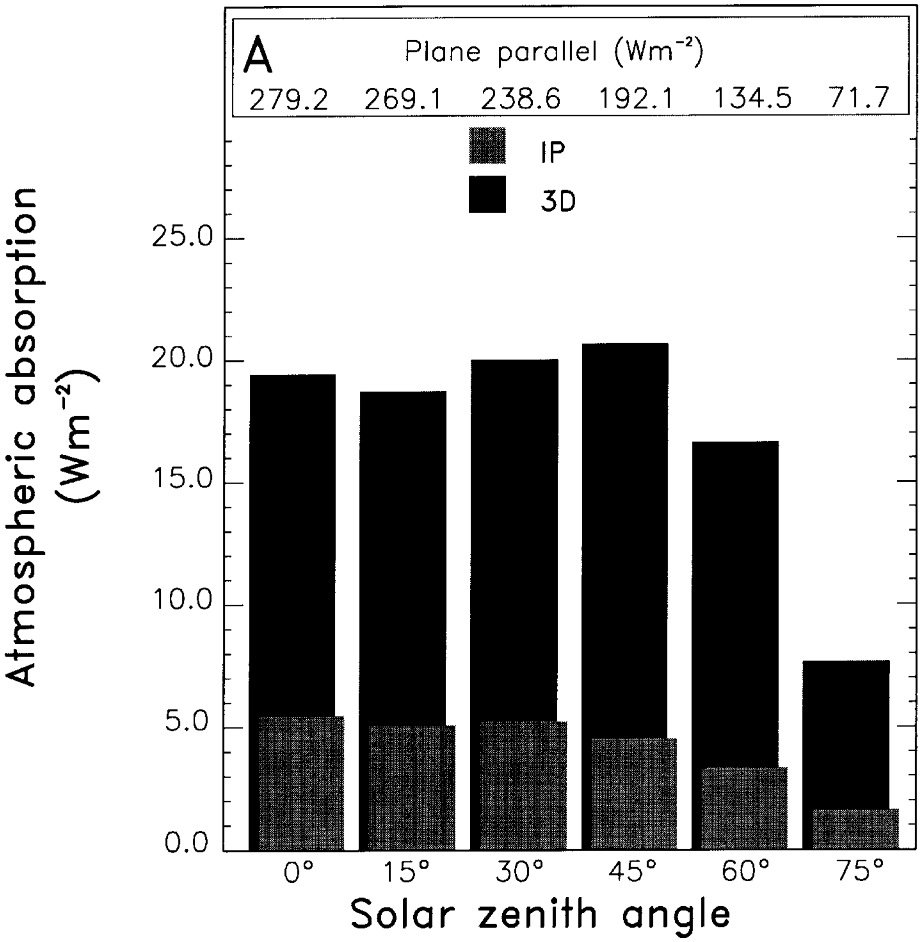

Figure 2. Atmospheric column broadband (0.25-4.0 µm) absorption deviations from plane parallel cloud for IP and 3D modes.

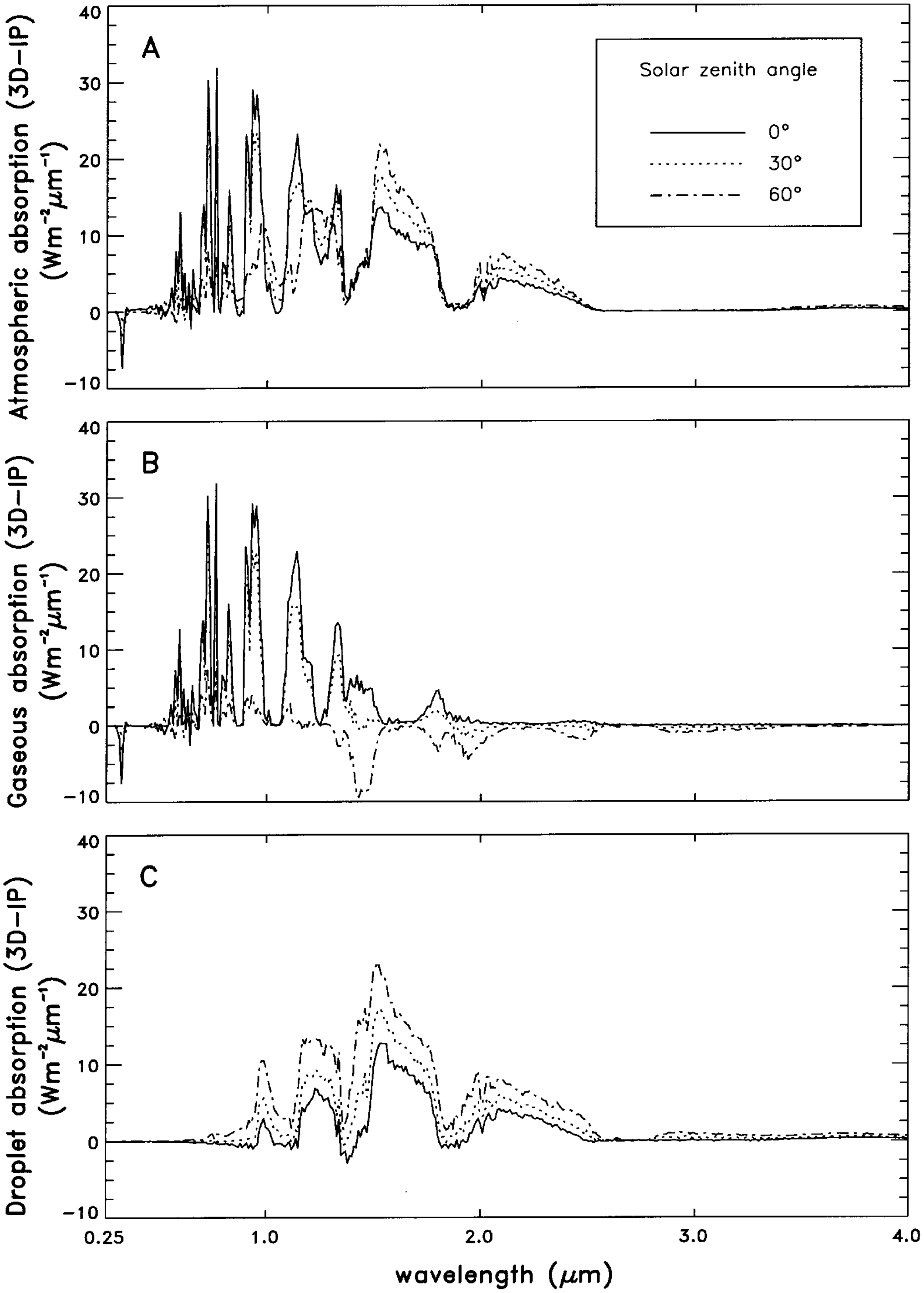

Figure 3. Difference (3D-IP) mode computations at each wavelength band. (A) Total atmospheric absorption (gas, aerosol, and cloud), (B) gaseous atmospheric absorption and (C) cloud droplet absorption.

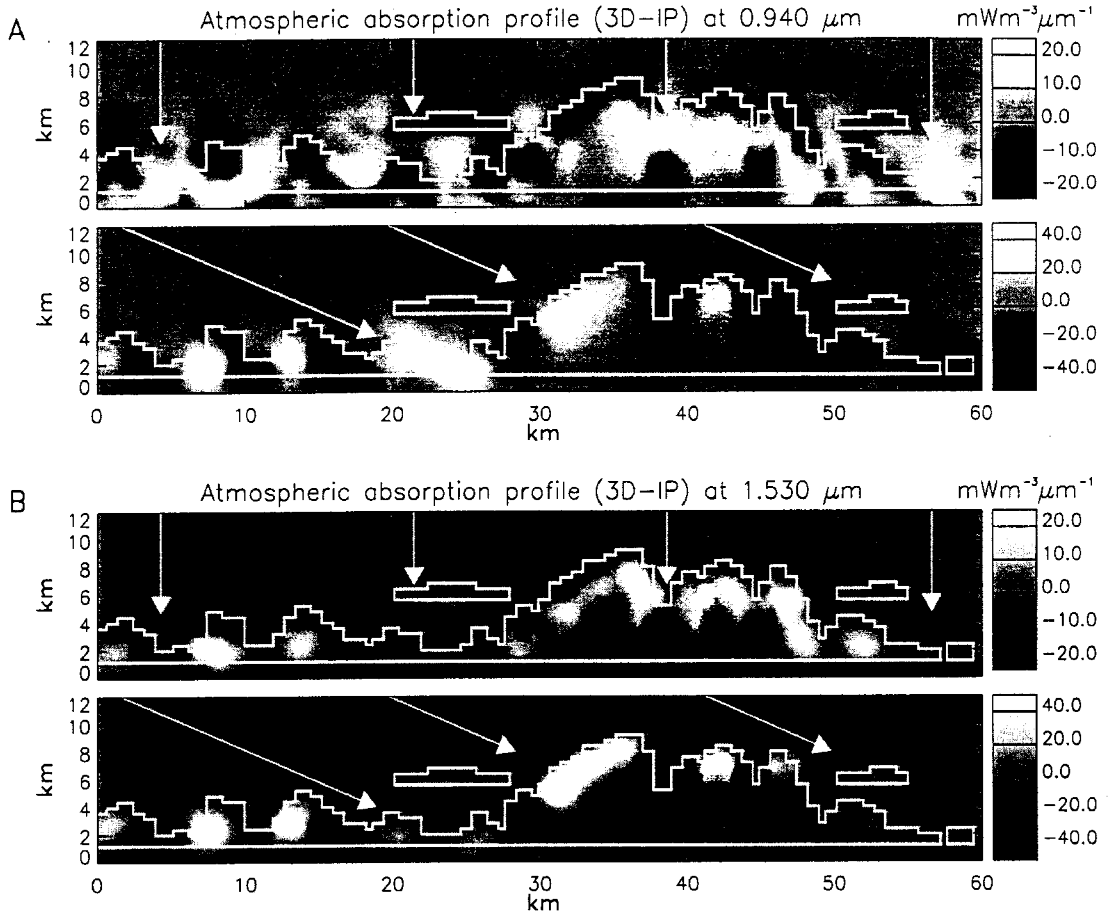

Figure 4. Vertical cross-section along 30-km east-west transect for (3D-IP) mode computations. Total atmospheric absorption at (A) 0.940 µm and (B) 1.53 µm, both for 0 and 60 solar zenith angle represented by vertical and slanted direct solar beam arrows, respectively. Heavy white line represents cloud outline.