A Multilayer, 1-D Solar Radiative Transfer Algorithm that Accounts for Subgrid-Scale Cloud Variability

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Abstract

A multi-layer, one-dimensional (1-D) solar radiative transfer algorithm that accounts for subgrid-scale cloud variability is presented. This algorithm was implemented in the National Center for Atmospheric Research (NCAR)-Community Climate Model (CCM) broadband column model. A subset of its validation is shown here using a three-dimensional (3-D) inhomogeneous cloud field generated by a cloud-resolving model. Reference calculations were obtained by a 3-D Monte Carlo (MC) simulation. The new code operates on horizontally averaged information, such as cloud fraction, mean, and variance of cloud optical depth, and reduces plane-parallel, homogeneous (PPH)-biases for top of atmosphere (TOA) albedo and surface absorptance by typically more than 85%. Moreover, its estimates of atmospheric heating rate usually differ from MC values by less than 10%.

Introduction

Numerous studies have demonstrated that fluctuations in cloud structure at scales less than about 10 km or so have large impacts on domain-averaged radiative fluxes (e.g., Wielicki and Parker 1992; Cahalan et al. 1994). Large-scale models (LSMs) of earth's atmosphere have horizontal grid-spacings that are typically between 50 km to 500 km. Thus, with the exception of cloud fraction, LSMs do not resolve most of the cloud fluctuations important for calculation of radiative fluxes. As such, both subgrid-scale radiative properties of clouds and radiative transfer must be parameterized.

The purpose of this abstract is to present a 1-D solar radiative transfer model, suitable for use in LSMs, that accounts for horizontal and vertical cloud fluctuations. It is based on the assumption that horizontal variations in cloud optical depth τ can be approximated by a gamma density function and that domain-averaged radiative transfer is fairly insensitive to details of the 3-D structure of clouds (Barker 1996). Hence, the new model is referred to as the gamma-weighted two-stream approximation (GWTSA). Though presented here within the context of the NCAR-CCM radiative transfer model (Briegleb 1992), it can be, and has been adapted to other column models (Oreopoulos and Barker 1998).

The Multilayer GWTSA

Basically, the GWTSA is like other 1-D radiative transfer codes that are built on the adding principle (Liou 1992): it requires estimates of domain-averaged collimated and diffuse albedos and transmittances for each layer. However, instead of computing these quantities with a regular PPH two-stream approximation, they are computed as

$$\left.\begin{matrix} R[p(\tau)] \\ T[p(\tau)] \\ r[p(\tau)] \\ t[p(\tau)] \end{matrix}\right\} \equiv \int_0^\infty p(\tau) \left\{\begin{matrix} R_{pph}(\tau) \\ T_{pph}(\tau) \\ r_{pph}(\tau) \\ t_{pph}(\tau) \end{matrix}\right\} d\tau, \qquad (1)$$

where R_{pph} and T_{pph} are PPH layer albedos and transmittance for direct-beam incident at a solar zenith angle of θ_0 (= $\cos^{-1}\mu_0$) r_{pph} and t_{pph} are corresponding solutions for a diffuse source, and $p(\tau)$ is a probability density function for τ across a layer. Barker et al. (1996, 1998a) and Oreopoulos and Barker (1998) demonstrated that, for the purpose of computing domain-averaged fluxes, $p(\tau)$ can be approximated well by

$$p_\Gamma(\tau) = \frac{1}{\Gamma(\nu)} \left(\frac{\nu}{\bar{\tau}}\right)^{\nu} \tau^{\nu-1} e^{-\nu\tau/\bar{\tau}}\ ;\ [\nu > 0], \qquad (2)$$

where $\bar{\tau}$ is mean optical depth and ν is a parameter that must be parameterized. Based on Landsat-inferred τ (Barker et al. 1996) and cloud-resolving model (CRM) data (Oreopoulos and Barker 1998; Barker et al. 1998a), adequate specification of ν may be simpler than one might suspect.

Substitution of both Eq. (2) and a suitable two-stream solution into Eq. (1) yields reasonably tractable expressions. However, direct use of these expressions in a straight-forward multilayer scheme is insufficient. Consider an overcast planar cloud that exhibits horizontal variability in τ, yet is correlated highly in the vertical. Though irradiated uniformly from above, all other radiation fields associated with this cloud lack horizontal homogeneity. Therefore, upon slicing this cloud into several layers and computing mean albedos and transmittances for each layer using Eq. (1), overall mean albedos and transmittances would lie between the true value and the corresponding PPH value: use of domain-averaged fluxes at each internal level represents a discrete step back towards the PPH solution.

To counteract this effect, mean optical depth of the *n*th layer $\bar{\tau}_n$ is reduced as

$$\bar{\tau}_n^* = \frac{\nu_n \bar{\tau}_n}{\nu_n + D(\mu_0) \sum_{k=k_{top}}^{n-1} A_k \bar{\tau}_k / \mu_0}, \tag{3}$$

where k_{top} is the cloudtop layer (whose $\bar{\tau}$ is unaltered),

$$D(\mu_0) = 0.063\mu_0 (2 - \mu_0),$$

stems from approximating T_{pph} by Beer's Law, and

$$A_k = \begin{cases} (1 - C_k)^{-1}, & C_k \le 0.5 \\ C_k^{-1}, & C_k > 0.5, \end{cases} \tag{4}$$

is an empirical factor used to counter the effects of implicit random overlapping of layer cloud fractions C_k. A final adjustment is made assuming that clouds in adjacent layers are maximally overlapped while clouds in separate layers are randomly overlapped. Thus, only the portion of clouds in layer *n* that overlap with clouds above in layer *n* - 1 have their optical depths reduced:

$$\bar{\tau}_n' = \begin{cases} \dfrac{C_{n-1}\,\bar{\tau}_n^* + (C_n - C_{n-1})\,\bar{\tau}_n}{C_n}, & C_{n-1} \le C_n \\ \bar{\tau}_n^*, & C_{n-1} > C_n, \end{cases}$$

Details (of which many were omitted here) can be found in Oreopoulos and Barker (1998).

Validation

The GWTSA has been implemented in the NCAR-CCM's column radiation code. To validate this model, a 3-D broadband MC algorithm was developed that attenuates photons in exactly the same manner as the NCAR model. In fact, for overcast PPH clouds, the MC and the NCAR codes yield almost identical flux profiles.

While several cloud fields have been used to validate the GWTSA, only one is used here: a 3-D field of cloud liquid water from Grabowski et al.'s (1998) CRM simulation of GATE-III. The domain is (400 km)^2, horizontal gridspacing is 2 km, and there are 35 layers of varying thickness. Figure 1 shows a plan view of its total τ (assuming 10 μm for droplet effective radius). Tropical profiles of CO_2 and

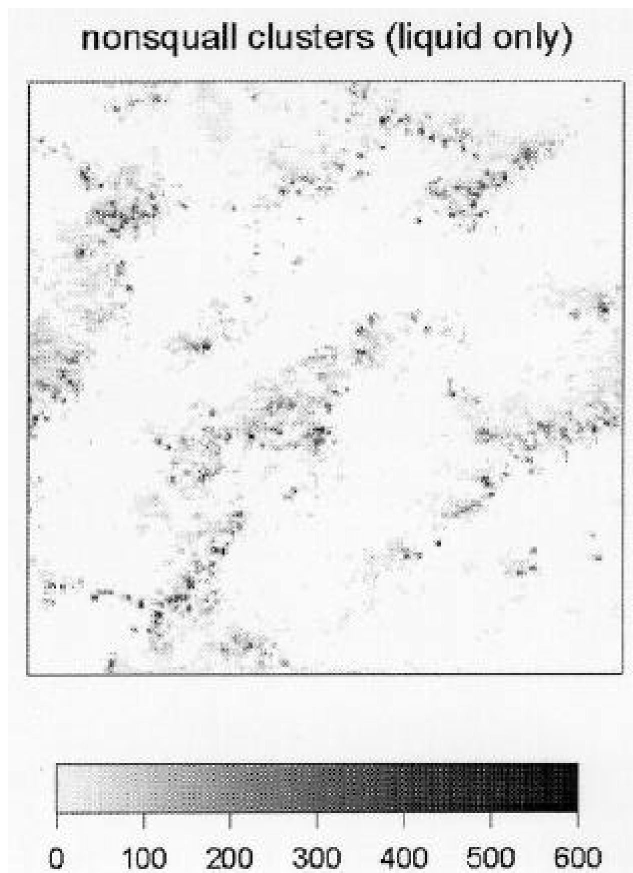

Figure 1. Distribution of cloud τ for a (400 km)^2 cloud field generated by a CRM.

O_3 were included as was Rayleigh scattering. The underlying Lambertian surface had a spectrally invariant albedo of 0.1.

To demonstrate the impact of explicit 3-D structure of this field (which has some towering clouds extending from ~2 km to ~12 km), the independent column approximation (ICA) was used. This is simply the application of the standard NCAR column model to each of the 40,000 columns in the field and averaging fluxes over the domain. Both the GWTSA and the original NCAR models operate on domain-averaged profiles of cloud fraction, $\overline{\tau}$, and (for the GWTSA) $\overline{\ln\tau}$.

Figure 2 shows broadband TOA albedos and surface absorptances as a function of μ_0. Clearly, the standard NCAR column model (NCAR) overestimates TOA albedo and underestimates surface absorptance greatly relative to the MC. The ICA underestimates TOA albedo for all μ_0, which is peculiar for it usually exceeds the MC for large μ_0 (see Barker et al. 1998b). Nevertheless, note that the ICA curves are almost parallel with the MC curves except for small μ_0. This is due to interception of photons by cloud sides which is represented only in the MC simulations. However, as energy levels are quite low in this regime, it is safe to say that explicit 3-D effects are rather minor.

While the GWTSA has exceeded its expectation (i.e., to close the gap between NCAR and MC), it differs from MC values by only about 10% to 20%. This represents removal of a sizable portion of the infamous PPH-bias; especially with respect to the surface energy budget. It is worth noting, though not shown here, that results for the effective thickness approximation (the ETA reduces layer $\overline{\tau}$ to $e^{\overline{\ln\tau}}$; Cahalan et al. 1994) are roughly halfway between the MC and NCAR curves. Atmospheric absorptances are also not shown because they all agree fairly well.

Figure 3 shows domain-averaged heating rate profiles for the four models at two values of θ_0 (60° and 0°). Excellent agreement is demonstrated between the ICA and MC for both sun angles though the MC shows slightly greater heating between 500 mb and 600 mb for $\theta_0 = 60°$ due to cloud side illumination. Likewise, the GWTSA does a remarkably good job at reproducing the MC profiles. Had it not been for the reductions to $\overline{\tau}$ via Eq. (3), GWTSA results would have been quite close to those of the ETA (which again are roughly halfway between those of NCAR and MC). In fact, values of $\overline{\tau}'/\overline{\tau}$ in the lower portions of cloud fields similar to those shown in Figure 1 (in this case, below ~700 mb) are typically less than 0.2 (at least a five-fold reduction in $\overline{\tau}$). In essence, the reduction of $\overline{\tau}$

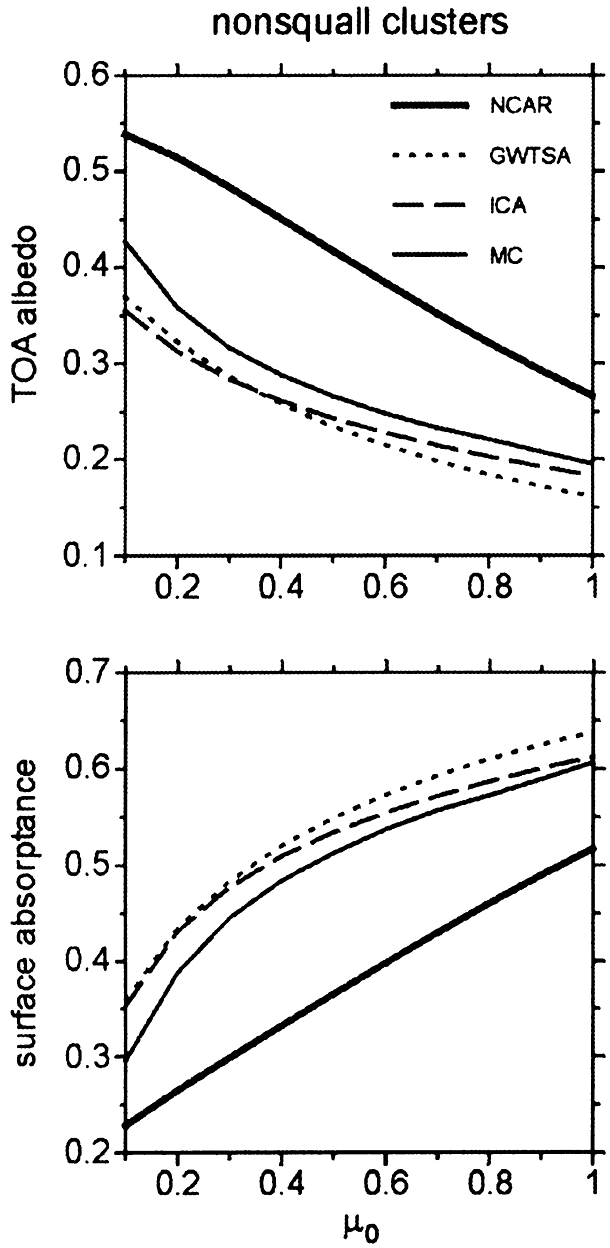

Figure 2. Broadband TOA albedo and surface absorptance as a function of μ_0 for the cloud field shown in Figure 1. Results are for four models as listed on the plot.

conveys to the 1-D code the fact that for partly cloudy skies, irradiance levels are very small inside clouds near the base of thick clouds; hence, do not even inform the radiation model that the clouds are there.

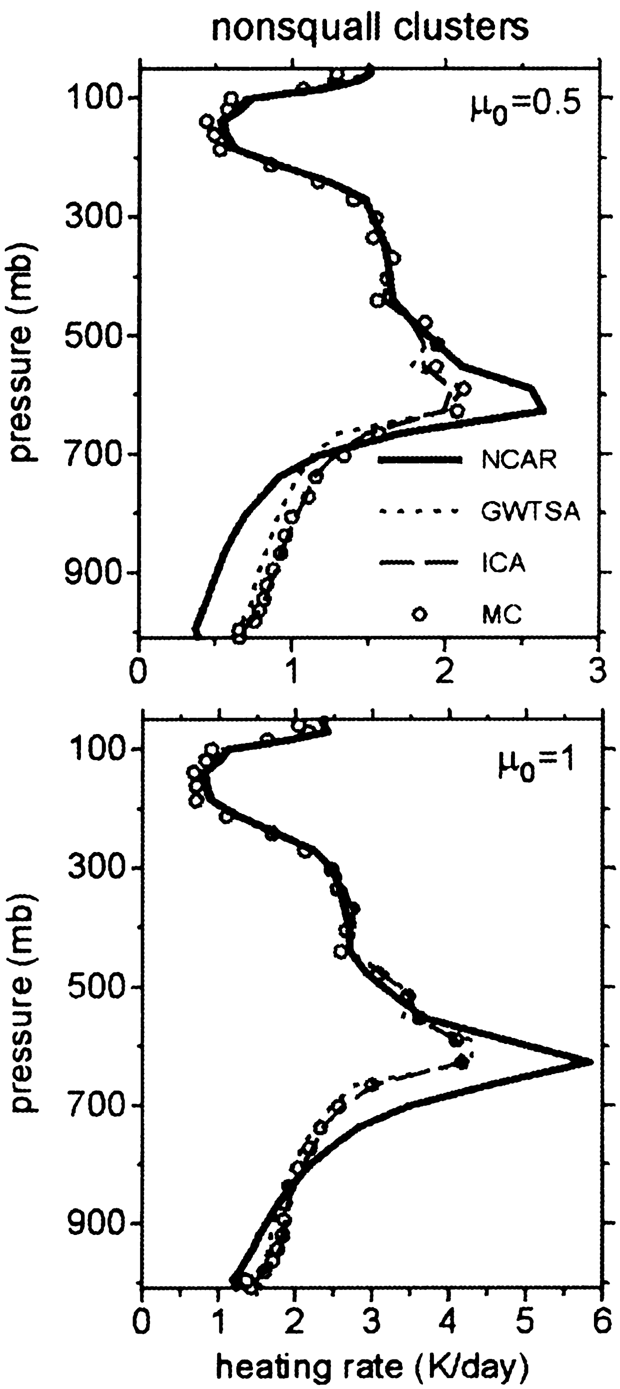

Figure 3. Broadband heating rates for two values of μ_0 for the cloud field shown in Figure 1. Results are for four models as listed on the plot.

On the other hand, the original NCAR model shows a substantial overestimation of absorption at primary cloud-bearing altitudes near 600 mb (~4 km). This is due to excessive absorption by exaggerated PPH cloud tops (Barker et al. 1998a,b). Conversely, the NCAR model exhibits weak heating below 800 mb (~2 km) as a direct result of its clouds being too reflective.

Summary and Recommendations

A 1-D solar radiative transfer algorithm was presented here that accounts for unresolved horizontal fluctuations in cloud optical depth τ. This algorithm is based on the assumption that frequency distributions of τ can be described adequately by the gamma density function and that explicit account of 3-D cloud effects is unnecessary. Basically, layer mean radiative properties are obtained by weighting a standard two-stream solution with the gamma distribution and integrating over all τ (hence, the model is referred to as the gamma-weighted two-stream approximation GWTSA). Also, to counteract use of mean fluxes, layer mean τ are reduced progressively from cloud top to base.

The GWTSA was implemented in the NCAR-CCM radiation code and validated using distributions of cloud derived from 3-D CRMs. Benchmark fluxes were produced by a 3-D MC photon transport algorithm that computes absorption as in the NCAR code. Domain-averaged profiles of cloud fraction τ and ln τ were computed and passed to the GWTSA. Typically, the GWTSA reduces flux and heating rate biases inherent to the original NCAR model by more than 85%. One area of the code that needs improvement is treatment of overlapping fractional cloud [see Eq. (4)]. A slightly different incarnation of the GWTSA is being tested presently in the Atmospheric Environmental Service's (AES's) weather forecast model.

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References

Barker, H. W., 1996: A Parameterization for computing grid-averaged solar fluxes for inhomogeneous marine boundary layer clouds. Part I: Methodology and homogeneous biases. *J. Atmos. Sci.*, **53**, 2289-2303.

Barker, H. W., B. A. Wielicki, and L. Parker, 1996: A parameterization for computing grid-averaged solar fluxes for inhomogeneous marine boundary layer clouds. Part II: Validation using satellite data. *J. Atmos. Sci.*, **53**, 2304-2316.

Barker, H. W., J.-J Morcrette, and G. D. Alexander, 1998a: Broadband solar fluxes and heating rates for atmospheres with 3D broken clouds. *Q. J. R. Meteorol. Soc.*, in press.

Briegleb, B. P., 1992: Delta-Eddington approximation for solar radiation in the NCAR Community Climate Model. *J. Geophys. Res.*, **97**, 7603-7612.

Cahalan, R. F., W. Ridgway, W. J. Wiscombe, T. L. Bell, and J. B. Snider, 1994: The albedo of fractal stratocumulus clouds. *J. Atmos. Sci.*, **51**, 2434-2455.

Grabowski, W. W., X. Wu, M. W. Moncrieff, and W. D. Hall, 1998: Cloud-resolving modeling of cloud systems during phase III of GATE. Part II: Effects of resolution and the third spatial dimension. *J. Atmos. Sci.*, in press.

Liou, K.-N., 1992: Radiation and cloud processes in the atmosphere. Oxford University Press, New York, 487 pp.

Oreopoulos, L., and H. W. Barker, 1998: Accounting for subgrid-scale cloud variability in a multi-layer, 1D solar radiative transfer algorithm. *Q. J. R. Meteorol. Soc.*, in press.

Wielicki, B. A., and L. Parker, 1992: The determination of cloud cover from satellite sensors: The effect of sensor spatial resolution. *J. Geophys. Res.*, **97**, 12,799-12,823.

Other Publications in Progress

Barker, H. W., G. L. Stephens, and Q. Fu, 1998b: The sensitivity of domain-averaged solar fluxes to assumptions about cloud geometry. *Q. J. R. Meteorol. Soc.*, submitted.