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# INCORPORATING CORRELATIONS BETWEEN OPTICAL THICKNESS AND DIRECT INCIDENT RADIATION IN A ONE-DIMENSIONAL RADIATIVE TRANSFER ALGORITHM

Seiji Kato*
Center for Atmospheric Sciences
Hampton University, Hampton, Virginia

## 1. Introduction

The difficulty of including height dependent cloud fraction and realistic overlap feature in a one-dimensional radiative transfer model arises because the irradiance emerging from the top and bottom of a cloud layer depends on both optical properties of cloud and the incident radiation (Stephens, 1988). An ordinary two-stream radiative transfer model that only computes the domain averaged irradiance at each computational level does not have enough information to treat the correlation between optical properties of layer and the incident radiation.

It seems that the most dominant correlation is that clouds receive more direct solar radiation when there is no clouds above them than when they overlap with high level clouds. As pointed out by Gabriel and Evans (1996), if the model compute the direct solar radiation properly, it can produce a fairly accurate domain averaged irradiance because the direct irradiance is either a large part of the domain averaged irradiance or a dominant source of the diffuse irradiance.

In this paper, a one-dimensional radiative transfer model that can treat the correlation to compute the direct irradiance is discussed. The irradiance vertical profile computed by the proposed model is compared with that computed with a Monte Carlo Model.

## 2. Direct Irradiance

In addition to inputs that are required for an ordinary two-stream radiative transfer model, the proposed model inputs the height dependent cloud fraction and cumulative cloud fraction computed from the top of the atmosphere to the surface. The cloud fraction is defined as the fraction of the vertically projected cloudy area to the area of the domain. Similarly, the cumulative cloud fraction of $j$th layer is the fraction of the vertically projected cloudy area including layers from the top of the atmosphere and bottom of the $j$th layer to the area of the domain

In order to compute the direct irradiance, the proposed model separates the direct irradiance in two components traveling in clear and cloudy columns. The clear column contains no cloud from the top of the atmosphere to surface and cloudy column contains clouds somewhere in the column. The domain averaged irradiance for a given level is a sum of direct irradiances in these two columns weighted by their fractional areas. Since the model computes the direct irradiance in two columns, four different clear and cloudy combinations at each leave are possible, (1) clear below clear (2) cloudy below cloudy (3) cloudy below cloudy and (4) clear below cloudy.

Therefore, the direct irradiance is further divided into four components. The diffuse irradiance of a clear part at each layer is computed using (1) and (4) components of direct irradiance as the source while the diffuse irradiance of a cloudy part is computed using (2) and (3) as the source.

## 3. Diffuse Irradiance

Let four components of the direct irradiance discussed in the previous section be $F_1^d$, $F_2^d$, $F_3^d$, and $F_4^d$. The direct irradiance incident on the clear part of $j$th layer is $F_{1j}^d$ and $F_{4j}^d$ and the irradiance incident on the cloudy part is $F_{2j}^d$ and $F_{3j}^d$. A two-stream solution of radiative transfer equation is set up for clear and cloudy parts using respective optical properties. Then the diffuse irradiance at any given level is the sum of the diffuse irradiance of clear and cloudy part weighted by the fractional area of each part. Using boundary conditions that match the diffuse irradiances at neighboring layer leads to a tridiagonal matrix that can solve for the diffuse irradiance at each level. One key assumption to form a tridiagonal matrix is the diffuse irradiance incident on the clear and cloudy part of a given level relative to the total diffuse irradiance at the level. The relation is required since the boundary condition is for the sum of diffuse irradiances of clear and cloudy parts (total diffuse irradiance). In this model, it is assumed that the diffuse irradiance incident on a layer is uniform. Therefore, clear and cloudy parts receive the same amount of diffuse irradiance.

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* Corresponding author address: Seiji Kato, Mail Stop 420, NASA Langley Research Center Hampton, VA 23681-2199; e-mail s.kato@larc.nasa.gov.

In summary, key assumptions in the proposed radiative transfer model are

1) Independent column (pixel) assumption (Stephens et al. 1991; Cahalan, 1994)
2) The cloud optical thickness distribution for a given layer follows a gamma distribution (Barker, 1996; Kato et al, 2001)
3) Clear and cloudy parts for a given layer receive different amount of the direct irradiance depending on clouds above the layer but receive uniform diffuse irradiance at the boundary (downward diffuse irradiance at the top boundary and upward diffuse irradiance at the bottom boundary).

## 4. Results

As shown in Figure 1, heating rates computed by the proposed one-dimensional radiative transfer model agrees with those computed by a Monte Carlo model for four different cloud fields shown in Figure 2. These four different cloud fields are generated by cloud resolving models and used for InterComparison of Radiation Codes in Climate Models (ICRCCM-III) (Barker et al. 2002). Clouds are ranging from stratocumulus clouds to deep tropical convective clouds. Results indicate that the proposed one-dimensional radiative transfer model produces a reasonable heating rates for these limited cloud cases compared with those computed by a Monte Carlo model.

On Figure 1, the heating rate computed by the same model but assume horizontally homogeneous clouds (labeled PP) is also plotted. Therefore, it uses only the average optical thickness of clouds in a layer instead of using a gamma distribution to compute radiation through clouds. In addition, Figure 1 also shows that the heating rate computed with the random cloud overlap assumption. It is computed with an adding model using transmittance and reflectance of each layer obtained by linearly mixing clear and cloudy parts of transmittance or reflectance weighted by their fractional area. Figure 1 shows that the proposed model improves the heating rate compared with that is computed with the random cloud overlap assumption.

In addition, Figure 3 and 4 shows the albedo at the top of the atmosphere and the net surface absorption divided by the downward irradiance at the top of the atmosphere as a function of solar zenith angle. It shows that the random cloud overlap assumption produces too large albedo at the top of the atmosphere and too small surface absorptance because the assumption produces too large cloud fraction for the domain. It also shows that the importance of horizontal inhomogeneity of cloud in the heating rate computation increases with cloud fraction since the larger difference between with and without the gamma-weighted two-stream approximation can be seen for the GATE B case.

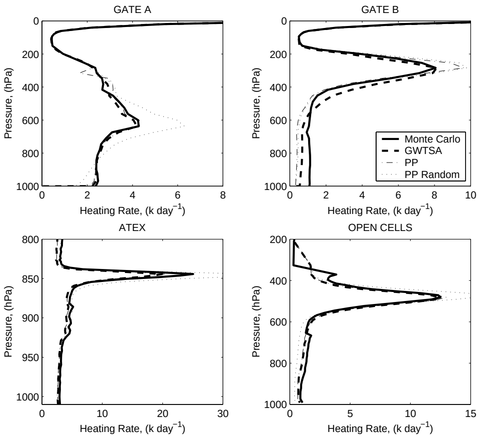

**Figure 1** Heating rate computed by a Monte Carlo model (solid line), by the clear and cloudy column method with the gamma weighted two-stream approximation (dashed-line), without the gamma weighted two-stream approximation (dash-dot line), and by a two-stream model with the random cloud overlap assumption (dotted line) for four different cloud fields used in ICRCCM-III (Barker et al. 2002). The solar zenith angle is 0° and surface albedo is 0.2.

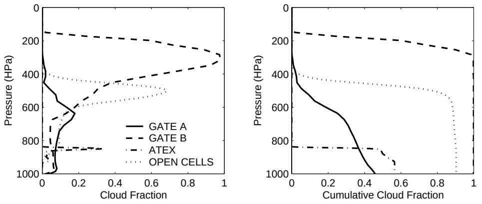

**Figure 2** Cloud fraction (left) and cumulative cloud fraction (right) as a function of altitude expressed by the pressure. Cloud fraction is the vertically projected cloudy area on a horizontal plane divided by the area of the domain. The cumulative cloud fraction is computed from the top of the atmosphere toward the surface. These cloud fields that were generated by cloud resolving models were used in ICRCCM-III (Barker et al. 2002). ATEX (Stevens, 1998), OPEN CELLS (Anderson et al. 1997), GATE A, and GATE B (Grabowski et al. 1998) are marine stratocumulus, convective clouds, cluster of tropical deep convective clouds, and squall line, respectively.

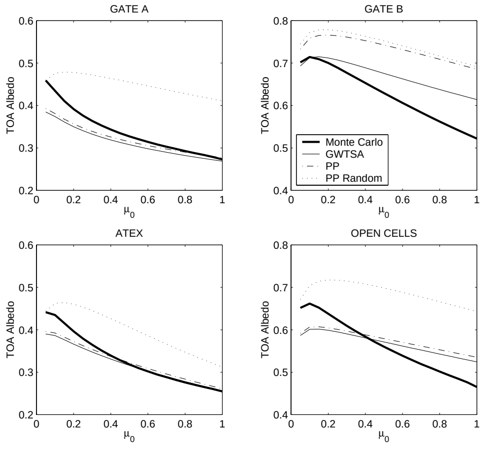

**Figure 3** Top of the atmosphere albedo computed by a Monte Carlo model (thick solid line), by the clear and cloudy column method with the gamma weighted two-stream approximation (thin solid line), without the gamma weighted two-stream approximation (dash-dot line), and by a two-stream model with the random cloud overlap assumption (dotted line) as a function of cosine of the solar zenith angle for four different cloud fields used in ICRCCM-III (Barker et al. 2002). The surface albedo is 0.2.

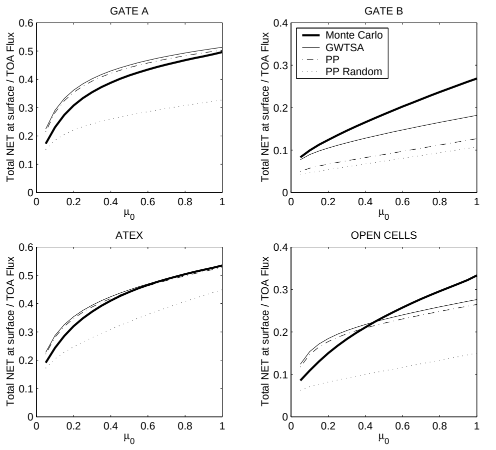

**Figure 4** Net absorption by the surface divided by the downward irradiance at the top of the atmosphere computed by a Monte Carlo model (thick solid line), by the clear and cloudy column method with the gamma weighted two-stream approximation (thin solid line), without the gamma weighted two-stream approximation (dash-dot line), and by a two-stream model with the random cloud overlap assumption (dotted line) as a function of cosine of the solar zenith angle for four different cloud fields used in ICRCCM-III (Barker et al. 2002). The surface albedo is 0.2.

## 5. Summary

This paper demonstrated that the heating rate computed by the proposed one-dimensional radiative transfer model agrees with that computed with a Monte Carlo model for four different cloud fields generated by cloud resolving models. It significantly improves shortwave radiative transfer computations compared with a two-stream model with the random cloud overlap assumption.

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