Cloud 3D effects on broadband heating rate profiles:
I. Model simulation

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ABSTRACT

Solar broadband heating directly drives the atmospheric and ocean circulations, and is largely determined by cloud spatial 3-dimensional (3D) structures. To study the cloud 3D effects on radiation, a 3D broadband Monte-Carlo radiative transfer model, along with an Independent Pixel/Column Approximation (IPA) method, is used to simulate radiation and heating rate of three typical cloud fields generated by cloud resolving models (CRM). A quantitative and statistical estimation of cloud 3D effects has been developed to investigate the impact of cloud 3D structures on both heating rate strength, \( STD_{Bias} \), and vertical distribution, \( CorrCoef \). The cloud 3D structures affect some clouds more in heating rate strength and others more in vertical distribution. It is crucial to use the combination of \( CorrCoef \) and \( STD_{Bias} \) for better quantitative evaluation of the 3D effects. Furthermore, there is no simple way to define a critical resolution (or average radius), within which the IPA heating rate profiles closely represent the true 3D heating rate profiles. The critical radius (or resolution) strongly depends on solar incident angle as well as cloud vertical distribution. Also, the critical radii for clear-sky columns are larger than for cloudy columns, although the corresponding \( STD_{Bias} \) for clear-sky columns are smaller than for cloudy columns. Analysis based on two different statistical average methods illustrates that the cloud 3D effects due to the dimensionality difference between the 3D clouds (circle average) and 2D clouds (line average) significantly impact on the heating rate profiles.

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1. Introduction

Clouds play a critical role in the balance of the atmospheric energy budget and hence in earth's climate system [1–4]. The climate system converts solar radiation into heat and the heating directly drives the atmospheric and ocean circulations. The incomplete knowledge of clouds, radiative forcing, and cloud feedback limits our understanding of detailed mechanisms of climate change [5]. It is well known that the distributions of heating rate profiles strongly depend upon the cloud three-dimensional (3D) vertical structures [6–8]. Therefore, to understand the effects of cloud 3D structures on broadband heating rate profiles is crucial to understand cloud feedback in the climate system.

Since General Circulation Models (GCM) treat cloud–radiation interaction with Plane-Parallel and Homogeneous (PPH) assumption, the impact of cloud 3D distributions on radiative transfer calculation is neglected in the large scale grids. Several studies demonstrated the bias of this simple PPH assumption to the real 3D situation [9–12]. The Independent Pixel/Column Approximation (IPA/ICA) method is considered to be a better approach than PPH in predicting the domain average
radiative properties [13–16]. However, the IPA method
neglects radiation horizontal transport, which results in
remarkable bias when clouds have complicated structures
[14,17–22].

Many efforts of investigating 3D cloud effects are
focused mainly on the large scale or domain average
results [10,22–29]. For example, Barker et al. [10,23]
showed that the domain averaged heating rate profiles
depend fairly weakly on cloud geometry. However,
Hinkelman et al. [22] argued that cumulus cloud geome-
try can cause changes of 10–17% in domain average
heating rate profiles. Fu et al. [29] pointed out that for a
cluster of deep convective cloud systems, the average
daytime absorption derived from full 3D simulation is
more than 20 W m−2 day more than the IPA estimate.

As GCMs and Cloud Resolving Models (CRM) are
improved in spatial resolution, it is necessary to assess
the cloud 3D effects under high resolution conditions [30–
33]. O’Hirok and Gautier [34] demonstrated that 2–5 km
is a critical resolution for cloud 3D effects. When a model
resolution is larger than this threshold for their selected
cases, the IPA approach is accurate enough. Di Giuseppe
and Tompkins [35] also found that the geometry-related
effects can have a larger influence on radiative transfer
calculations than internal optical inhomogeneity for the
CRM resolved tropical deep convective clouds.

Most of those studies are focused on the surface or the
top of the atmosphere (TOA) radiation fluxes. However,
the radiation closure at the boundaries cannot ensure the
accuracy of the heating profile [36]. The erroneous heating
rate distribution due to the simplification of RT calcula-
tion would impact on cloud formation and dynamics. Also
cloud 3D effects are an important issue for remote
sensing. Hence, with improving model and measurement
spatial resolutions, more attention should be paid to the
cloud 3D effects on the vertical distribution of heating
rate. As the first of our series researches, this work will
focus on a quantitative assessment of the cloud 3D effects
on heating rate profiles, particularly from both modeling
and observational perspectives. With the basic under-
standing and evaluation of the 3D effects on heating rate
profiles, we will seek ways to detect the 3D effects in
addition to current imaging instruments or vertical
resolved active sensors in the follow-on research.

2. Cloud fields and radiative transfer model

2.1. CRM cloud fields

Three CRM-resolved cloud fields, named as ATEX,
Open-cells, and GATE-A, are selected from the InterCom-
parison of Radiation Codes in Climate Models (ICRCCM)
program phase III and used in our radiation simulation.
Fig. 1 illustrates their main optical properties. They are
typical cloud fields with different cloud patterns, domain
areas, and resolutions, enabling a comprehensive study of
the impact of cloud 3D effects on heating rate profiles.
Although some clouds are mixed phase clouds, they are all
treated as water droplets with effective radius of 10 μm to
simplify the calculation. These simplifications are the
same as done in ICRCCM [37]. ATEX (Fig. 1a) is generated for the Atlantic Trade Wind
Experiment (ATEX) [37]. It is a marine boundary layer
cloud which extends from about 0.7 to 1.6 km. The
horizontal resolution is 0.1 km and the domain size is
(6.8 km)2. The vertical resolution varies from 0.02 to
0.04 km in the cloudy parts. Most clouds locate around
1.5 km and the average extinction coefficient β is about
100 km−1. The cloud fraction A decreases at lower
layers while β increases to about 200 km−1.

GATE-A (Fig. 1b) is extracted from the simulation of
phase III of the Global Atmospheric Research Progra-
m—Atlantic Tropical Experiment (GATE) [38]. This cloud
consists of non-squall clusters of organized convection
with the anvil removed so as to mimic towering or
developing clouds. The deep convective clouds extend up
to 8 km in this field. The horizontal resolution is 2 km
and the domain size is (400 km)2. The vertical resolution
varies from 0.2 km to several km. The typical β is about
60 km−1. Both geometric and optical depths are thick in
this cloud field.

The Open-cells (Fig. 1c) represent a cold-air outbreak
over warm water, consisting of strong open cellular
convection clouds [39]. Vertical and horizontal resolu-
tions are 0.15 and 0.39 km, respectively. The entire cloud
field is about (50 km)2. The main layer locates between 4
and 7 km, with a lower thick cloud layer at about 2 km.
The extinction coefficient β is about 30 km−1 for the
upper-layer clouds, and about 70 km−1 for the low-level
clouds.

2.2. Radiative transfer model

We use a broadband 3D Monte-Carlo radiative transfer
model to calculate broadband SW radiation. The spectral
range is from 50,000 to 2500 cm−1. Non-gray gaseous
absorptions, including H2O, CO2, O3, CH4, and N2O, are
parameterized based on the correlated k-distribution
method, with 54 bins in 6 SW bands [40]. The other
details of the model are described by Barker et al. [10].
The IPA calculations use the same 3D model by setting
the horizontal resolution as infinite in each column, ignoring
the horizontal transport between the columns. Both true
3D Monte-Carlo simulation and IPA calculation will
simply be referenced by 3D and IPA.

All three cloud fields are simulated at 10 solar zenith
angles (SZA) with an interval of cosine (SZA) of 0.1 for
domain average calculation and validation, and at 4 SZAs
of 0°, 30°, 45°, and 60° for detailed heating rate
calculation. Both 3D and IPA approaches are calculated
for comparison. The solar azimuth angle is 0°. The surface
albedo is set to be a constant of 0.2. Sufficient photons are
emitted to ensure the convergence for the Monte-Carlo
simulation.

Before detailed analysis, our 3D results are validated
against the benchmark of the ICRCCM, which is the
average result from several 3D models [37]. Fig. 2a and b
shows the domain average transmittances with differ-
ent SZAs and the domain average heating rate profiles
at SZA of 60° SZA for all three cloud fields, respectively.
The validation shows a good agreement between our results and the benchmark.

3. Statistical parameters and methods

3.1. Statistical parameters

To evaluate the vertical distribution of heating rate, two parameters, \( \text{CorrCoef} \) and \( \text{STD} \_\text{Bias} \), are used to quantify the similarities and differences between each pair of heating rate profiles. They are very similar to the traditional definitions of correlation coefficient and standard deviation, with some modifications for the current application.

For a given pair of profiles, vectors \( HR_{3D}(n) \) and \( HR_{IPA}(n) \) where \( n \) is from 1 to \( N \) and \( N \) is the layer of the profile, we calculate the covariance matrix \( \text{Cov} \) by

\[
\text{Cov}(HR_{3D}, HR_{IPA}) = E[(HR_{3D} - \mu_{3D})(HR_{IPA} - \mu_{IPA})]
\]

where \( E \) is the mathematical expectation and \( \mu_{i} = EHR_{i} \).

The CorrCoef is calculated by

\[
\text{CorrCoef} = \frac{\text{Cov}(HR_{3D}, HR_{IPA})}{\sqrt{\sigma_{3D}^{2}\sigma_{IPA}^{2}}}
\]

where \( \sigma_{i} \) is the variance and \( \sigma_{i} = E(HR_{i} - E(HR_{i}))^{2} \). The CorrCoef quantifies the similarity of the two vertical profiles.
To define the difference between the two vertical profiles, we first calculate the parameter STD defined as

\[ STD = \sqrt{\frac{\sum_{i=1}^{n} (HR_{3D}(i) - HR_{IPA}(i))^2}{n}} \]  

(3)

Then the STD_Bias is defined as

\[ STD\_Bias = \frac{STD}{HR_{3D}} \times 100 \]  

(4)

where \( HR_{3D} \) is the mean of the relative 3D heating rate. The STD_Bias is the percentage of the bias to the mean value of the 3D heating rate. Considering the heating rates of three cloud fields are compared together, the STD_Bias is better than the STD to quantify the relative difference between the two vertical profiles. Combination of these two parameters not only describes the deviation of the heating rate strength, but also directly represents the vertical properties of the heating rate.

3.2. Statistical methods

Two statistical methods are applied to show the cloud 3D effects on the heating rate profiles: Method I (Circle statistics) and Method II (Line statistics). The schematic of Method I is shown as the left panel in Fig. 3. For each column, the average radius changes from 1 column to 20 columns to get 20 circle areas for different resolutions. In each circle area, two average heating rate profiles over the area are calculated by both 3D and IPA approaches. And then the CorrCoef and STD_Bias between these two profiles are obtained. For each radius (or resolution), the statistical mean CorrCoef and STD_Bias of all columns within the simulation domain are calculated. Note that the spatial resolution is twice the corresponding radius. This scenario represents a statistical average in most applications in numerical models and satellite imager/scanning measurements.

Many observations, fixed-view sensors at both surface and satellite, cannot obtain all the data in a domain area. To mimic this kind of observation, we use Method II (Line statistic). The radius still changes from 1 column to 20 columns for each column, but only columns along a line through this central one will be included in our statistical analysis. We set the line’s azimuth to be the same as the solar incidence angle (0°). The schematic of Method II (Line statistic) is shown as right panel in Fig. 3. The rest of the statistical processes are the same as Method I.

Fig. 2. (a) Validation of domain average transmittances changing with SZA between our results and the ICRCCM benchmark of three cloud fields. (b) Similar validation of average heating rate profiles at 60° SZA. The solid lines are our results and the dashed lines are the benchmarks. Different cloud fields are marked by different symbols.

Fig. 3. Schematic of two statistical methods. Left panel shows Method I and right panel shows Method II.
4. Results

4.1. Domain average results

Before proceeding into detailed analyses, we first studied the domain average results. Fig. 4 shows the comparison of domain averaged transmittance, reflectance, and absorptance between the 3D and the IPA. In general, the IPA results reasonably agree with the 3D results. The IPA tends to be more transmissive (less reflective) at low SZA, and less transmissive (more reflective) at larger SZA than the 3D, regardless of the cloud fields, as the IPA neglects the cloud side leakage for overhead sun and the cloud side illumination for low sun. Furthermore, the IPA column absorption is always less than the 3D with the maximum bias at an intermediate SZA. Such bias patterns can be explained by the lack of horizontal transport in the IPA approach. The horizontal fluxes always increase photon path length, resulting in an increase of column absorption for the 3D. Clearly, the bias in the Open-cells case is relatively larger than the other cases. As the Open-cell cloud field has more broken structures, more photons are trapped between cloudy pixels, thus accumulating water vapor absorption.

The bias in the heating rate profile varies with SZA and is more obvious at high SZA value, shown in Fig. 5. Vertically, the largest heating rate bias in current simulations occurs within the clouds where cloud fraction is maximum in the profiles as shown in Fig. 1. At the lower altitude under this part, the bias is increasing when the sun is more oblique, as more photons penetrate into clouds and are scattered into horizontal transport that enhances the atmospheric absorption.

4.2. Heating rate profile with different statistical methods

Different average radius and/or methods would result in different heating rate profiles, particularly for high resolution applications. Fig. 6 shows an example, a subset of the Open-cells cloud field, to illustrate the cloud 3D effects for various methods with different radius. Simulation is done for SZA at 45°. The central column, the column (37, 52) in the Open-cells domain, is a multi-layer cloud (Fig. 6b), with some multi-layer clouds and some single high-level clouds around it (Fig. 6a). The mean heating rate profiles at different average radius for Methods I and II are shown in Fig. 6c and d, respectively. The results of Method I indicate that, for small radius (e.g., \( R = 2 \)), the lack of horizontal transport in the IPA results in the overestimation of heating rate at the upper-layer cloud and underestimation at the lower-layer cloud, with respect to the 3D heating rate profile and much worse to the central column heating rate profile. As clouds

![Fig. 4. Domain average transmittance (a), reflectance (b), and absorptance (c) of three cloud fields at different SZAs. The solid and dashed lines represent the 3D and the IPA, respectively. Different cloud fields are marked by different symbols.](image-url)
clustered with many upper-level clouds, the vertical distribution of average profiles converges to the upper layer in a short range. On the other hand, the heating of lower layer disappears for large average radii, as more single high-level clouds occurred in the ranges. The lack of heating of lower layer compared to the 3D results would certainly change the evolution of the low-level clouds, and consequently the entire cloud system. In general, it is clear that the vertical distributions of heating rate of the IPA are getting closer to those of the 3D with increasing average radius in both methods. In Method II, due to the limit of samples and the dimensionality difference, there is a substantial difference between the Methods I and II, in both the 3D and the IPA.

To illustrate the cloud 3D effects on inhomogeneous distribution of heating rate, we mimic the observation along the satellite track or time series of a surface observation. Fig. 7 is a slice view for the Open-cells case with SZA of 45°. All results are calculated by Method II. In a range of 40 km, the cloud field is composed by clear-sky, thick convective clouds, and thin clouds (Fig. 7a). Comparing the 3D and IPA results in Fig. 7b and c, there is an obvious illuminating-effect towards the incident direction and shadowing-effect at the opposite direction at the top layers. Furthermore, the 3D results show an upward shift, which is consistent with the previous findings [34,35]. This ‘erroneous heating’ is further examined at different resolutions, shown in Fig. 7d and e. At a resolution of about 4 km (5 columns in radius), the average process does not significantly improve the heating rate profiles, i.e., the heating rate is still obviously underestimated in cloudy columns and overestimated in clear columns. At a resolution of about 10 km (12 columns in radius), one column may contain both clear-sky and cloudy atmosphere. At such a large average domain, the differences between the 3D and the IPA are substantially reduced. However, there is still some bias in vertical distribution, particularly in a column with thin and broken clouds from 24 to 34 km where the differences are still in a range from −2 to +2 k/day.

For high spatial resolution applications in either modeling or remote sensing, to ignore the cloud 3D effects and to directly use the averaged results of a large area would lead to substantial errors in local heating rate profiles. The solar radiation may heat some columns a few kilometers away from the correct ones. The shift of erroneous heating at lower layers is largely determined by solar incident angle and associated with photon horizontal transport. The tilted IPA (TIPA) [21,22] may be sufficient to deal with the shift associated with solar incident angle by calculating the photon transport in independent columns towards the direction of incident radiation. However, the lack of photons horizontal transport in the IPA or TIPA may still result in certain errors in the heating rate profile, even with a resolution of 10 km. The wrongfully heated columns certainly would affect the accuracy of model simulations and retrievals.
4.3. Statistical analysis

To quantitatively illustrate the cloud 3D effects, the statistical results are evaluated for all three cloud fields with various SZAs and the two average methods. Fig. 8 shows the mean CorrCoef and STD_Bias for Open-cells and GATE-A as a function of average radius. In general, the CorrCoef increases and the STD_Bias decreases with average radius. At the scale of about 5 km in radius in Open-cells (and 10 km in radius in GATE-A), the improvements in both CorrCoef and STD_Bias start to diminish, indicating the IPA bias in the heating rate profile cannot be completely eliminated. At such a scale, the photon horizontal transport dominates the bias. Also, the CorrCoef decreases and the STD_Bias increases with SZA, especially with small average radius. The difference

Fig. 6. A sample of smooth process in Open-cells at 45° SZA. (a) Cloud types around the central column (marked by symbol X), (b) the vertical distribution of cloud visible optical depth of the central column, (c) the averaged heating rate profiles for both the 3D and the IPA with different radii by Method I, and (d) the same as (c) but by Method II.
associated with SZA is reduced significantly with the average radius. However, the difference between Methods I and II increases with the average radius, due to the fundamental difference in dimensionality between the 3D clouds and the 2D clouds, and to a lesser extent, insufficient samples. It has serious consequences, as many derived heating rate profiles from observations with fixed view sensors, such as broadband heating rate profile (BBHRP) products from current atmospheric radiation measurement (ARM) facilities.

Our three cloud fields have distinct cloud structures as well as different domain and column resolutions.
As shown in Fig. 9, different cloud fields have distinct characteristics of 3D effects on heating rate profiles. In particular, we compared Open-cells and GATE-A, since they have comparable range. The Open-cells cloud field mainly consists of high-level clouds with some optically thick low-level clouds, resulting in a quite high CorrCoef, for a given average radius. The scattered high-level clouds allow some photons reaching the lower portion of the atmosphere and heating the low-level clouds. Due to its inherently physical defects, the IPA cannot accurately reproduce the magnitude of low-level heating, resulting in a large STD_Bias. The GATE-A cloud field is quite different from Open-cells, with more single-layer deep convective clouds. The 3D effects have greater impacts on the vertical distribution of heating rate with a smaller CorrCoef than on the heating rate strength with a better STD_Bias, with respect to the Open-cells. The ATEX with a better resolved cloud field has good CorrCoef and STD_Bias. Overall, it appears that the cloud 3D structures affect more in heating rate strength for ATEX and Open-cells, and more in vertical distribution for GATE-A.
Most previous studies used mainly the differences of strength between 3D and IPA to assess the 3D effects [34]. As we discussed above, the combination of CorrCoef and STD_Bias provides a better quantitative evaluation of the 3D effects. To better quantify the 3D effects, therefore, we set a threshold of CorrCoef at 0.99, and subsequently we seek its corresponding average radius and assess its associated STD_Bias in our three cloud fields. The CorrCoef threshold of 0.99 indicates that the IPA heating rate profiles are strongly correlated to the true 3D heating rate profiles. As listed in Table 1, for overhead sun, the critical radii of ATEX, Open-cells, and GATE-A are 0.16, 0.66, and 5.84 km, and the corresponding average STD_Bias values are 15.53%, 15.08%, and 5.08%, respectively. For the SZA of 60°, the critical radii are increased substantially to 0.83, 3.19, and 15.46 km, respectively. The ratios of critical radii at the two SZAs, 5.2, 4.8, and 2.6, respectively, depending on the averaged cloud top heights in the cloud fields, are larger than the slant path ratio (2) at the two SZAs. The STD_Bias values, on the other hand, are increased to 34.01%, 32.00%, and 6.72%, respectively.

These results corroborate the previous finding that the degree of cloud 3D radiative transfer effects strongly depend on solar incident angle. It is worth noting that some columns are excluded in sample numbers, as the CorrCoef for these columns cannot reach 0.99 within an averaged radius of 20 columns. Also, the critical radii for clear-sky columns are larger than for cloudy columns, and the corresponding STD_Bias values for clear-sky columns are smaller than for cloudy columns. It suggests that the clear-sky column heating rate profile is significantly affected by surrounding cloud structures, particularly at small spatial scales.

5. Summary and conclusions

In order to seek ways to detect the cloud 3D effects, we have to better understand and quantitatively assess the 3D effects on broadband heating rate profiles, from both modeling and observational perspectives. Beyond evaluating transmittance, reflectance, and absorption, we used two parameters, CorrCoef and STD_Bias, to quantitatively assess both vertical distribution and strength of heating rate profiles. Those heating rate profiles are calculated by the full 3D and IPA approaches in three cloud fields at different SZAs. Also, two statistical methods are applied to represent the modeling and observational characteristics at different average radii (or resolutions).

Our 3D results were first validated against the benchmark of the ICRCCM, and showed good agreement with the benchmark. Secondly, the domain averaged 3D effects on transmittance, reflectance, and absorption were assessed. It indicated that the IPA tends to be more transmissive (less reflective) at low SZAs, and less transmissive (more reflective) at larger SZAs than the

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>The effective radius (when the CorrCoef reaches 0.99), relative STD_Bias and samples of three cloud fields calculated by both methods at 0° and 60° SZA.</td>
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<table>
<thead>
<tr>
<th>Method I</th>
<th>Method II</th>
</tr>
</thead>
<tbody>
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<td>Cloudy</td>
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<td><strong>ATEX (784 Samples)</strong></td>
<td></td>
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<tr>
<td>0°</td>
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<tr>
<td>Radius (km)</td>
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<td>STD_Bias (%)</td>
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<tr>
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<tr>
<td>60°</td>
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</tr>
<tr>
<td>Radius (km)</td>
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<tr>
<td><strong>Open-cells (3844 Samples)</strong></td>
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<td>0°</td>
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<td>Radius (km)</td>
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<tr>
<td><strong>GATE-A (25,921 Samples)</strong></td>
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3D, and the IPA column absorption is always less than the 3D with the maximum bias at an intermediate SZA, regardless of the cloud fields. Those are consistent with previous findings, and can be explained by the lack of horizontal transport in the IPA.

The 3D effects on heating rate profiles are largely determined by cloud vertical structures. Low-level clouds and clear-sky pixels are affected the most, as the high clouds block the incident solar radiation for the shadowing-effect and/or reflect the incident solar radiation for the illuminating-effect. These processes are the primary reason for the heating rate shift, as well as for retrieval errors from satellite observations, particularly for high-resolution applications. Furthermore, as illustrated in both case and statistical analyses, the cloud 3D structures affect more in heating rate strength for the one set of cloud fields, such as ATEX and Open-cells, and more in vertical distribution for others, such as GATE-A. It is crucial to use the combination of CorrCoef and STD_Bias for better quantitative evaluation of the 3D effects.

From our quantitative statistical analysis, there is no simple way to define a critical resolution (or average radius), within which the IPA heating rate profiles closely represent the true 3D heating rate profiles. It is clear that the critical radius (or resolution) strongly depends on solar incident angle as well as cloud vertical distribution, such as the mean cloud top height. Also, the critical radii for clear-sky columns are larger than for cloudy columns, although the corresponding STD_Bias values for clear-sky columns are smaller than for cloudy columns. It suggests that the clear-sky column heating rate profile is significantly affected by surrounding cloud structures. Furthermore, the difference between Methods I (Circle average) and II (Line or a fixed view average) is increasing with the average radius. As many derived heating rate profiles from observations with fixed view sensors, such as BBHHP products from current ARM facilities, the cloud 3D effects due to the dimensionality difference between the 3D clouds and 2D clouds significantly impact on the heating rate profiles.

Our study is based on limited cloud fields and contains some assumptions in model setting. The issues raised in this study warrant more detailed studies, including wider spectral range [25,26,41]. The erroneous heating rate distribution due to the simplification of the RT calculation would certainly impact on cloud formation and dynamics. Hence, as the resolution of CRM and GCM models improves, the accuracy of the approximation algorithms such as the IPA should be reassessed, in terms of the cloud 3D effects on the heating rate profile and their impacts on cloud formation and atmospheric circulations. More importantly, observational capability is needed for detecting the 3D effects in addition to current imaging instrument or vertically resolved active sensors. As photon path lengths are controlled by spatial distributions of scattering and absorption, the information of photon path length distribution inferred from a high-resolution oxygen A-band spectrometer provides a measure of the 3D cloud effects [42–44]. Our follow-up study will focus on how to use the information of photon path length distribution to study the cloud 3D effects on heating rate profiles.

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Reference


