The Impact of Spatial Resolution on Model-Derived Radiative Heating

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Introduction

At the typical spatial resolution of climate and weather forecasting models, clouds are portrayed as uniform plane-parallel entities with three-dimensional (3D) radiative effects generally considered not important. However, as the resolution of these models increase, and with the development of "super parameterizations" (embedded cloud resolving models), there is a need to assess the spatial resolution where 3D effects should not be neglected (Khairoutdinov and Randall 2001). In this study, we perform 3D solar radiative transfer computations on four distinctively different cloud fields to understand the sensitivity of atmospheric heating rate profiles to the spatial resolution of the calculations.

Method

The cloud fields are derived from millimeter wave cloud radar (MMCR) observations as described in O'Hirok and Gautier (2003). The modeled atmosphere contains all radiatively important gases and oceanic aerosols with radiosondes providing profiles of temperature and humidity. For the surface an ocean albedo is specified. The 3D heating rate profiles are computed using a Monte Carlo radiative transfer model on a two-dimensional cloud field with variability along the vertical and a single horizontal axis. While the third axis has a constant optical thickness, a photon can travel in this direction and still encounter variations if the trajectory is not orthogonal to the other horizontal axis. To simulate typical plane-parallel radiative transfer models, computations are conducted in a one-dimensional (1D) mode where photons are confined to a single atmospheric column. All computations are made at a spectral resolution of 5 nm below 1 um and 10 nm above 1 um.

Figure 1 displays the liquid water content (LWC) and effective radius of the four cloud fields used in this study. Cumulus with a base of about 2 km makes up cloud field "A." Cloud field "B" has thick stratus with an average optical thickness of 24.3. Field "C" is composed of multiple layers of broken clouds. Convective clouds with overlying cirrus are simulated in cloud field "D." Each of these fields is

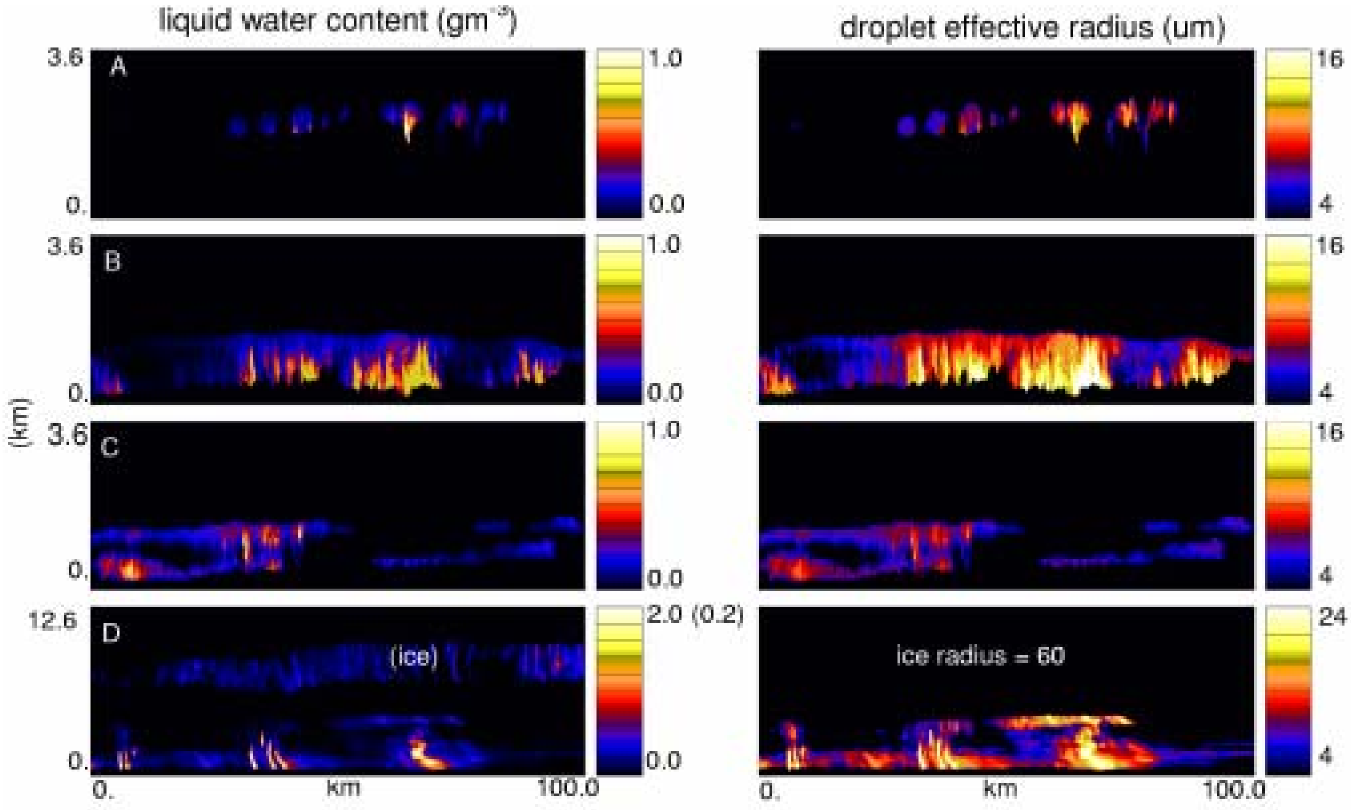

Figure 1. Model cloud fields derived from MMCR. Cloud field 'D' contains overlying cirrus with a mode radius of 60 um.

initially composed of 500 columns having a resolution of 200 m. These fields are progressively degraded until there are two columns of 50 km in size (Figure 2). A field of 100 km resolution is derived by partitioning the field into a cloudy and clear column with the cloudy column containing the average cloud property at each level. The averaging of the cloud droplet size is weighted by the LWC of each cell. The vertical resolution is held constant at 45 m with the exception of field "D," which has a resolution of 90 m.

The spatial scale where 3-D effects become important to heating rates is tested within the context of two scenarios. The first scenario represents a method to reduce the computational burden of employing a "super parameterization" within a General Circulation Model. In this case, the mean shortwave radiative heating for an entire domain, $1D_{(i)}$, where *i* is the domain size, is applied to each column of an embedded cloud resolving model. The error associated with this assumption is evaluated by examining the difference, $1D_{(i)} - 3D_{(200m)}$, where $3D_{(200m)}$, represents the true heating rate of each embedded atmospheric column. Differences found here will be caused by a combination of spatial smoothing and 3D radiative effects. The second scenario represents the case where the radiation is individually computed for each column, but assumes that there is no photon horizontal transport between the columns. The error associated with this method is determined for various column sizes by examining the difference $1D_{(i)} - 3D_{(i)}$.

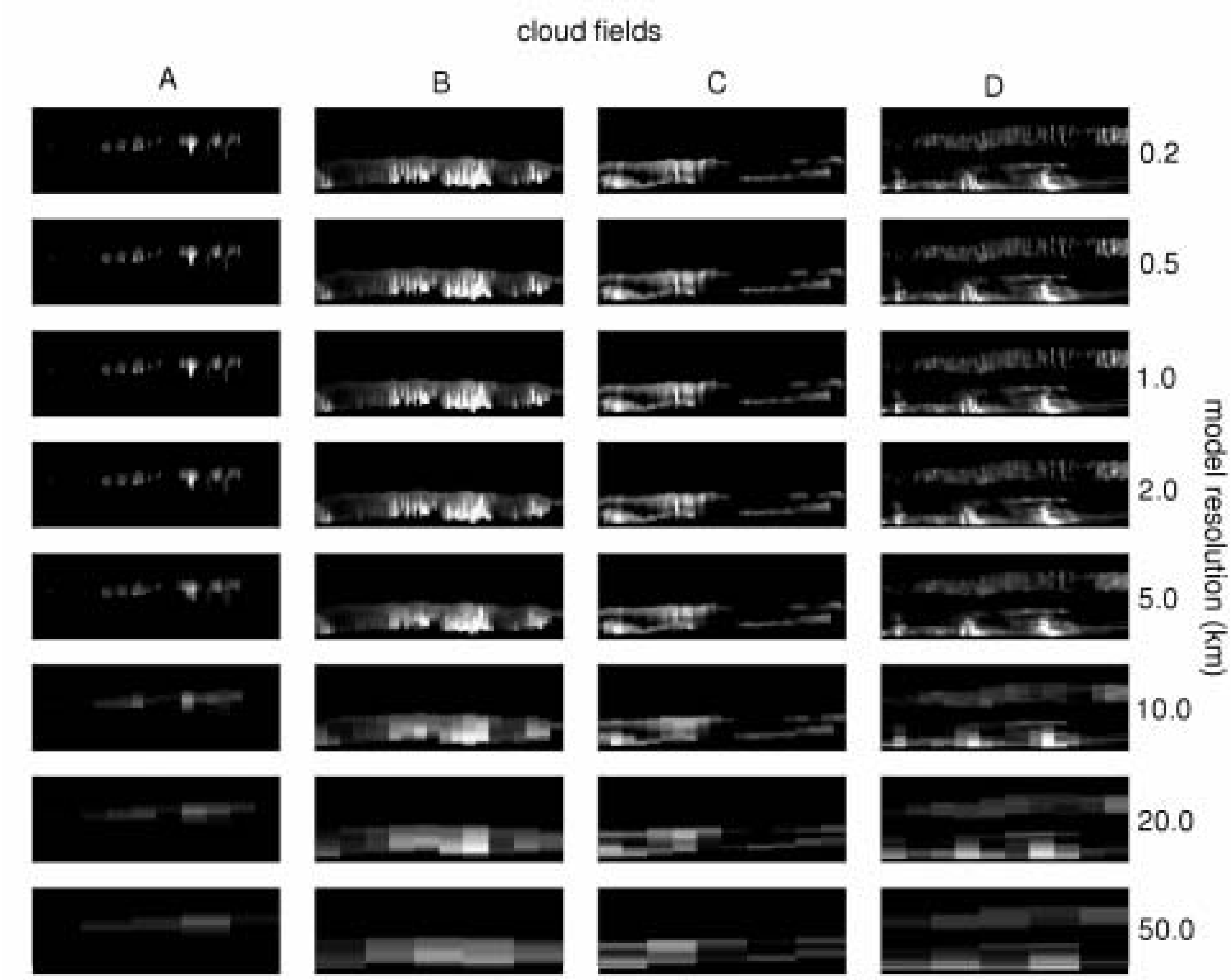

Figure 2. Spatial degradation of cloud fields.

For computing dynamics it is important to accurately derive the correct heating rate for each individual column rather than merely obtain a correct statistical mean for an ensemble of atmospheric columns. To evaluate this measure the heating rate errors are ranked and partitioned into percentile groupings. The ranking is determined for each layer individually, and thus a particular column may be classified within more than one percentile grouping. Within each percentile group, an average error is derived and plotted. The groupings are partitioned into -5, -20 -50, 100, 50, 20, and 5 percentiles with the negative results plotted in shades of blue and the positive in shades of red. The 100 % percentile (yellow) includes all columns and thus represents the domain average error.

Results

Sample images of the heating rate profiles for the 0.2 and 10 km fields are presented in Figure 3. At the highest resolution, the most pronounced feature of a 3D effect is the horizontal displacement of the solar beam. This shift produces clear differences in the location of the gaseous absorption below the clouds as shown for case “A” and absorption by the convective clouds located beneath the cirrus in case “D.” At 10 km resolution, the 3D effects are minimal with only small difference noticeable for case “D.”

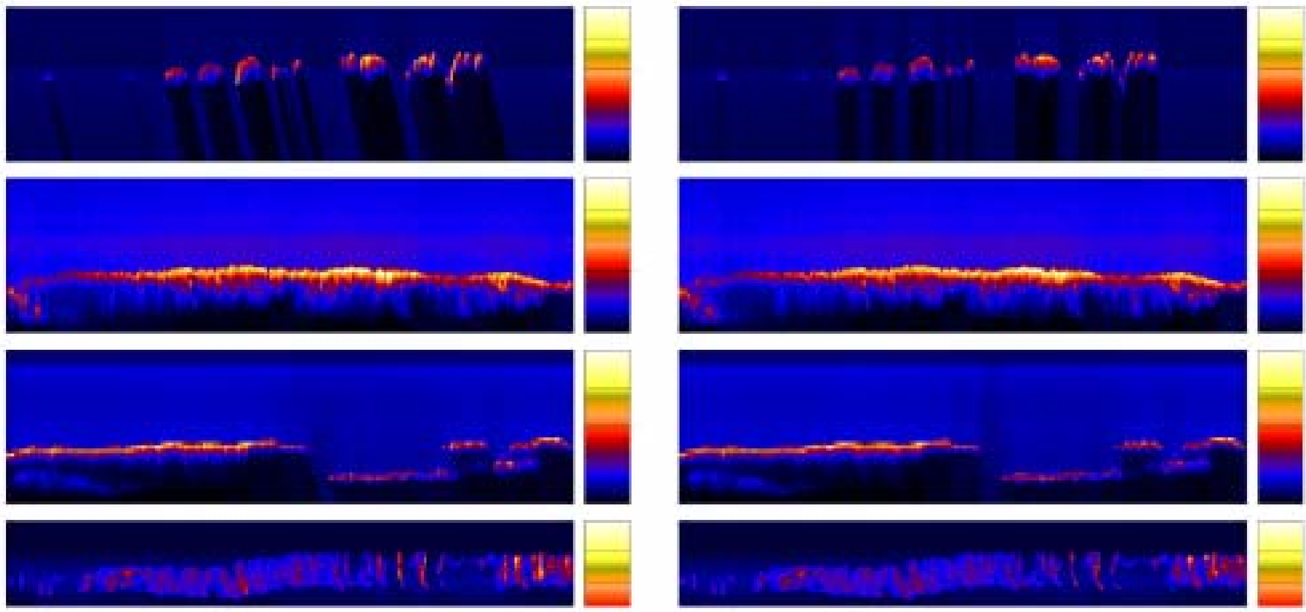

Figure 3. 3D and 1D heating rate for horizontal resolutions of 0.2 and 10.0 km. Computations are shown for a solar zenith angle (SZA) of 60°.

Figure 4a, representing the first scenario, plots the heating rate errors for SZAs of 0° and 60° with *i* set to 0.5, 2.0, 10.0, and 100.0 km. It is not surprising that the difference, $1D_{(i)}$ - $3D_{(200m)}$, increases as the domain size is expanded. This relationship is easily explained by examining cloud field “A.” For this cumulus cloud field values far less than -10K° per day are obtained for domain resolutions larger than 10 km. At a resolution of 200 m resolution many of the columns are cloud free allowing most of the solar radiation to reach the surface. However, as the spatial resolution decreases all the columns eventually become overcast to the extent that the solar radiation is now absorbed higher in the atmosphere throughout the entire domain. For most of these cases, the errors are caused the redistribution of the cloud properties and are not a result of 3D effects. Even for the initially overcast condition of field “B,” the decrease in resolution causes errors because of the small variations in the cloud top altitude that are reduced by smoothing. Similar results are found for the multilayered clouds of fields “C” and “D,” but the errors tend to occur throughout the vertical depth of the clouds because of their complex morphology. At a SZA of 60°, errors of a few K° are noticeable even when *i* is set to 500 m for the reason that 3D effects become increasing important at the higher resolutions.

Figure 4b shows the errors associated with the second scenario that examines the impact from neglecting photon horizontal transport. Whereas before errors became greater as the domain size increased, here the largest discrepancies occur for the highest resolutions. For the morphologically complex fields of “A” and “D,” the plane-parallel assumption can produce differences of between 3 and 4 K° per day at

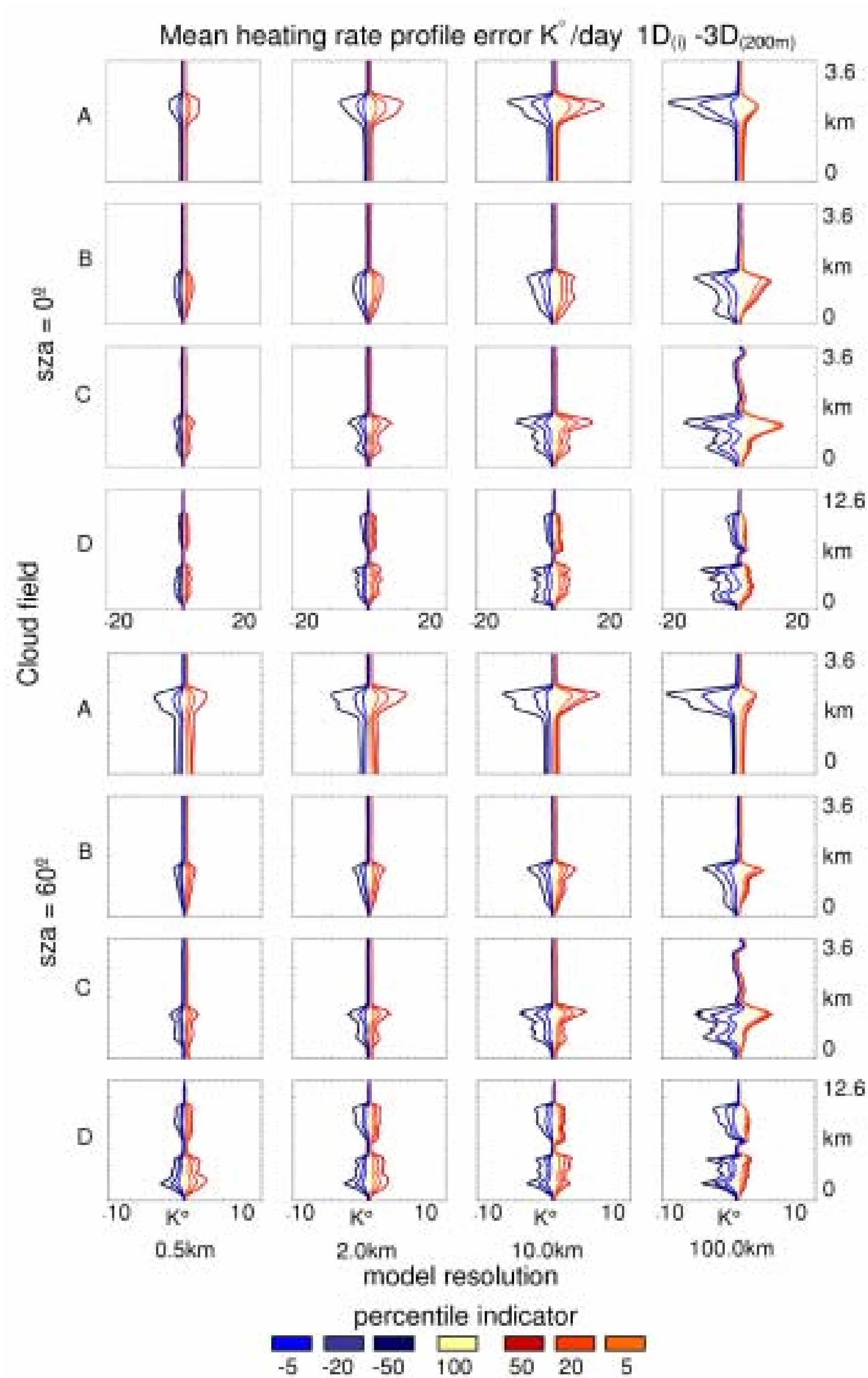

Figure 4a. Heating rate errors for scenario 1.

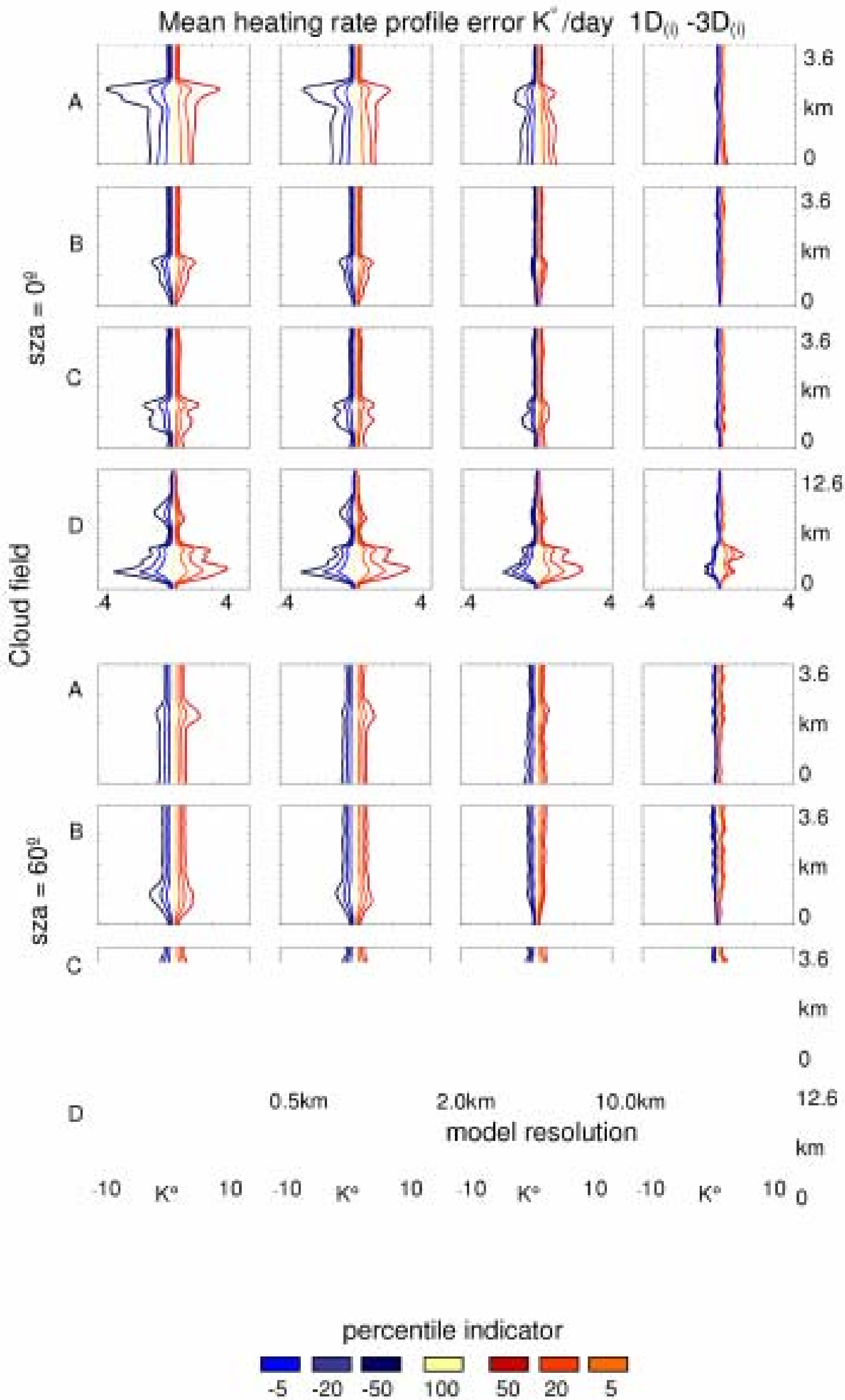

Figure 4b. Heating rate errors for scenario 2.

spatial resolutions better than 1 km. At a 2 km resolution, differences up to 2 K° per day are found within the convective cells of field "D." The layered clouds of fields "C" and "D" show less sensitivity to photon horizontal transport, but still there are errors of more than 1 K° per day at the cloud tops.

The impact of scale on the total atmospheric absorption for each embedded column is presented in Figure 5. Similar to Figure 4, the results are displayed as the mean atmospheric absorption for all columns classified within a particular percentile ranking. However, this figure differs from previous because an entire column may only be classified within a single percentile group. Each bar shown in the figure represents a different column size.

As found for the heating rate profiles in the first scenario, the difference between a 1D computation evaluated at resolution *i* and the "true" (3D) absorption can be significant and generally increases as the domain size is enlarged (Figure 5a). However, for cloud field "D" the absorption is relatively insensitive to the domain size. Here, photon horizontal transport compensates for the relatively weak impact of spatial smoothing at these higher resolutions. At the steeper sun angles, the errors for the layered cloud fields "B" and "C" remain constant because the 3D computation smoothes the cloud tops in a manner similar to mechanically degrading the fields.

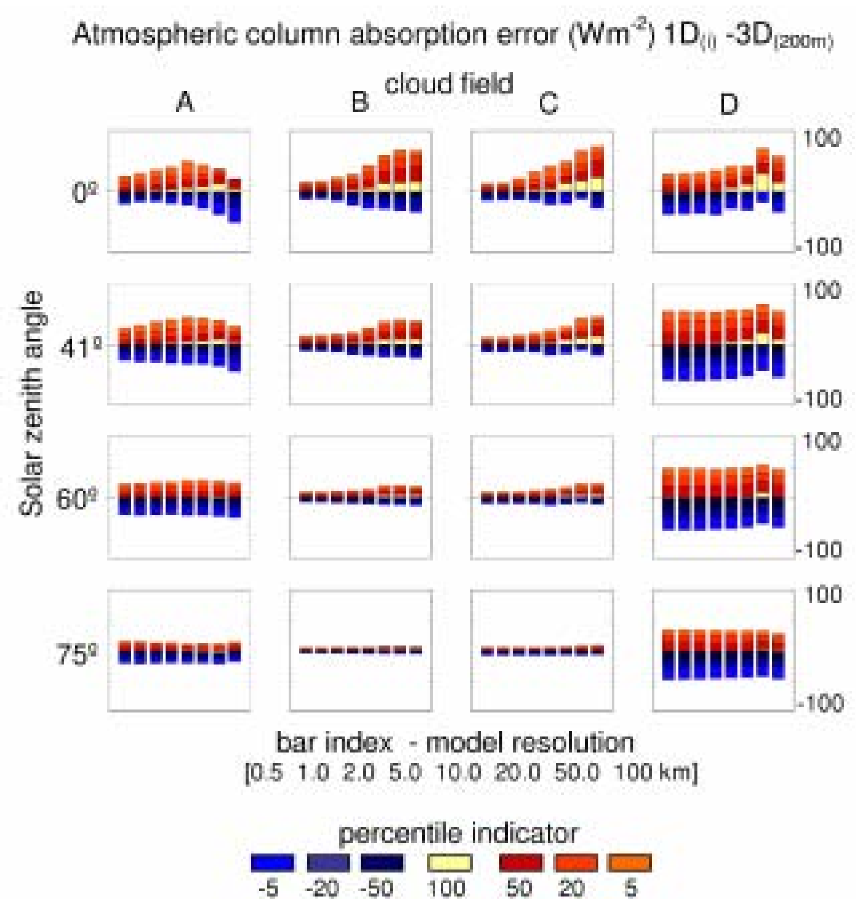

Figure 5a. Atmospheric column absorption error for scenario 1.

The impact of the plane-parallel assumption (second scenario) on atmospheric column absorption is presented in Figure 5b. Averaged over the entire domain, 3D effects are negligible at all computational resolutions. However, for individual columns at the highest resolutions 3D effects can be substantial. The $1D_{(i)}$ - $3D_{(i)}$ error is strongly a function of column resolution within the model domain. For all the fields except “D”, the column absorption becomes relatively insignificant for the columns larger than 2 km. For the convective field “D,” errors reach 30 Wm^{-2} for a column size up to 5 km. At the steeper SZAs, this error can represent 50% of the total atmospheric absorption occurring within a single column.

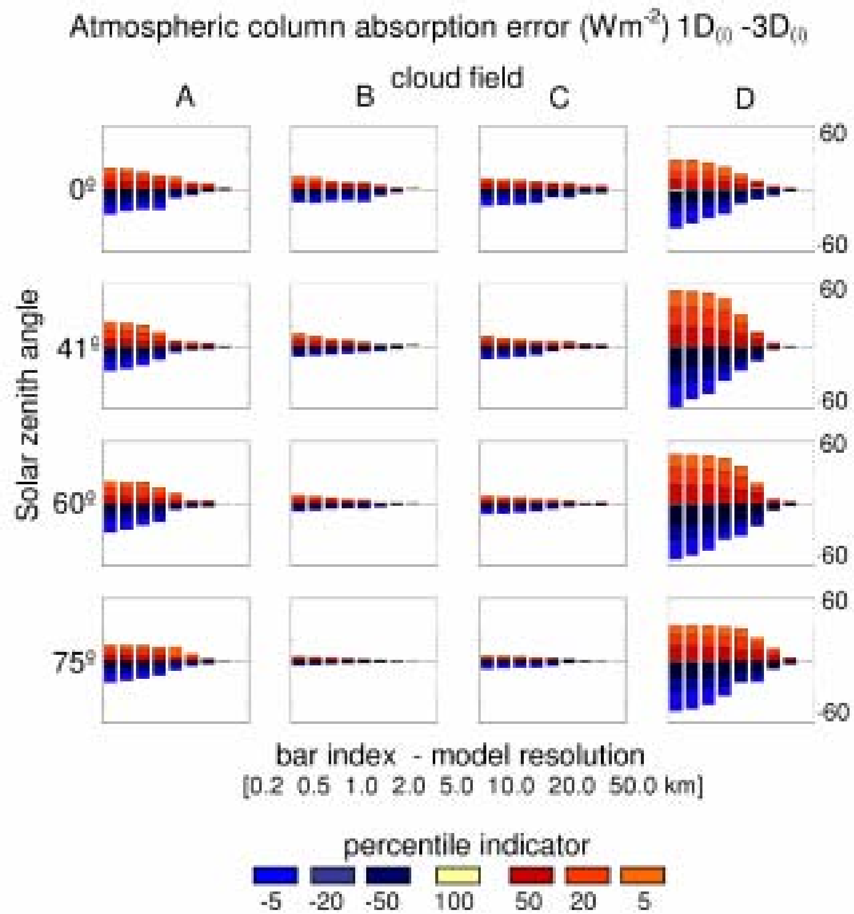

Figure 5b. Atmospheric column absorption error for scenario 2.

Conclusion

In this study, the impact of spatial resolution on model-derived shortwave radiative heating is presented within the context of two scenarios. The first assumes that a single domain average heating rate is applied to embedded columns within that domain. The results show that very large errors can be produced for individual columns. The tendency for these errors to increase with decreasing resolution suggests the need to compute radiative fluxes at space-time resolutions similar to those used to generate the cloud fields. The second scenario (and most relevant to most modeling endeavors) assumes that the dynamics and radiation are computed at the same spatial scale, but there is no photon horizontal transport. It is difficult to define a resolution where 3D effects should not be neglected because the errors need be evaluated within a cloud resolving model to determine the impact on cloud dynamics. However, for the limited cases presented, it may be suggested that for most layered clouds 3D effects should not be neglected for resolutions better than 2.0 km and this range should be extended to 5.0 or even 10.0 km for the morphologically complex fields.

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References

Khairoutdinov, M, and D. A. Randall, 2001: A cloud resolving model as a cloud parameterization in the NCAR Community Climate System Model: Preliminary Results. *Geophys. Res. Lett.*, **28**, 3617-3620.

O'Hirok, W., and C. Gautier, 2003: Absorption of shortwave radiation in a cloudy atmosphere: Observed and theoretical estimates during the second Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE). *J. Geophys. Res.*, in press.