The Sensitivity of Cloud Field Structure to Three Dimensional Radiative Effects

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Introduction

During the past decade, research has shown that while 3 dimensional (D) radiative effects are negligible at the horizontal resolution of GCMs, they can be significant at the scale of cloud resolving models. A common thread throughout these studies is the static framework in which they are performed - that is, computations are performed on cloud fields of fixed properties. They ignore the more salient issue of understanding the role of 3D cloud-radiative interactions on dynamics and their subsequent impact on cloud field structure and feedbacks. With the increasing use of cloud resolving models, it is essential to understand how these coupled processes propagate through high resolution cloud simulations. To investigate this topic we recently replaced the 1D shortwave radiative transfer code in the Weather Research and Forecasting model with one that solves for horizontal photon transport using the Monte Carlo method. However, before such a research tool can be used effectively it is necessary to establish the sensitivity of the model results to variations in spatial and temporal resolution and stochastic noise.

Model Computations

In this study, we performed a 2D simulation of a deep convecting cloud system over land using the Monte Carlo model to compute the heating rates without (i.e. 1D) and with horizontal photon transport (i.e. 3D). Currently, longwave radiative transfer is computed in 1D. For the reference computation, the column horizontal spatial resolution is set at 500 m with a domain size of 400 km. The simulation is performed for 240 minutes. The initial time-step for the radiation is 30 seconds. A cyclic boundary condition is employed for both the dynamics and the radiation. For the Monte Carlo computations, the average root-mean-square error (RMSE) of the heating rate for cloud tops (or peak optical thickness for clear sky) at individual columns is approximately 5%. Further details of the model can be found in O'Hirok et al. 2005.

Results

Presented in Figure 1 is a time-lapse composite of the cloud field profile for the first 80 minutes of the simulation at 10 minute intervals. Note the rapid expansion of the cloud field during the first 30 minutes. Within a static framework, it has been demonstrated that 3D radiative effects are enhanced as the horizontal resolution of a model is increased (O'Hirok and Gautier 2005). However, because small horizontal columns entail short integrations times the net impact of 3D radiative effects depends greatly on the movement speed of individual cloud parcels. Hence, for a rapidly moving cloud edge 3D effects are reduced by temporal averaging that is akin to the spatial averaging of the radiation. In Figure 2 the spread of the 3D heating over a two minute period is shown for simulation times of 25 and 57 minutes. Initially, the cloud expansion is rapid enough to diffuse any impact of enhanced heating. After about an hour, the slower cloud growth provides longer integrations for individual cloud elements. It is after this time that the first divergences appear between the 1D and 3D simulations for domain accumulated precipitation and average surface temperature (Figure 3). The cloud structure represented by the average condensate profiles reveals a similar pattern (Figure 4).

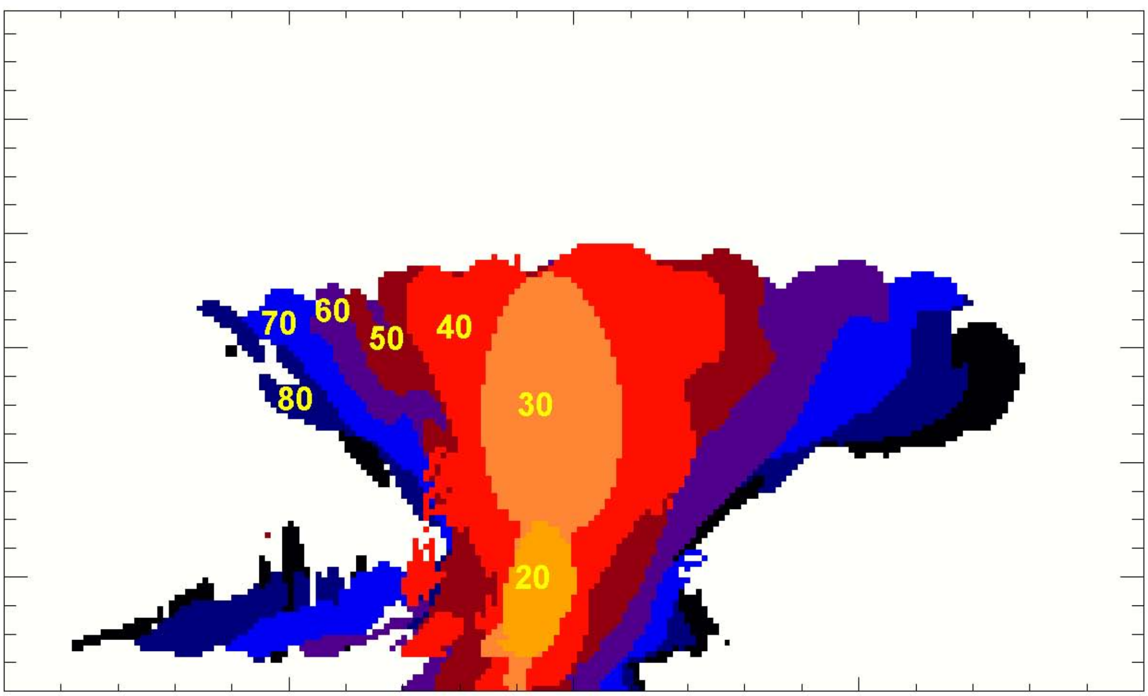

Figure 1. Cloud profile over first 80 minutes of simulation at 10 minute intervals.

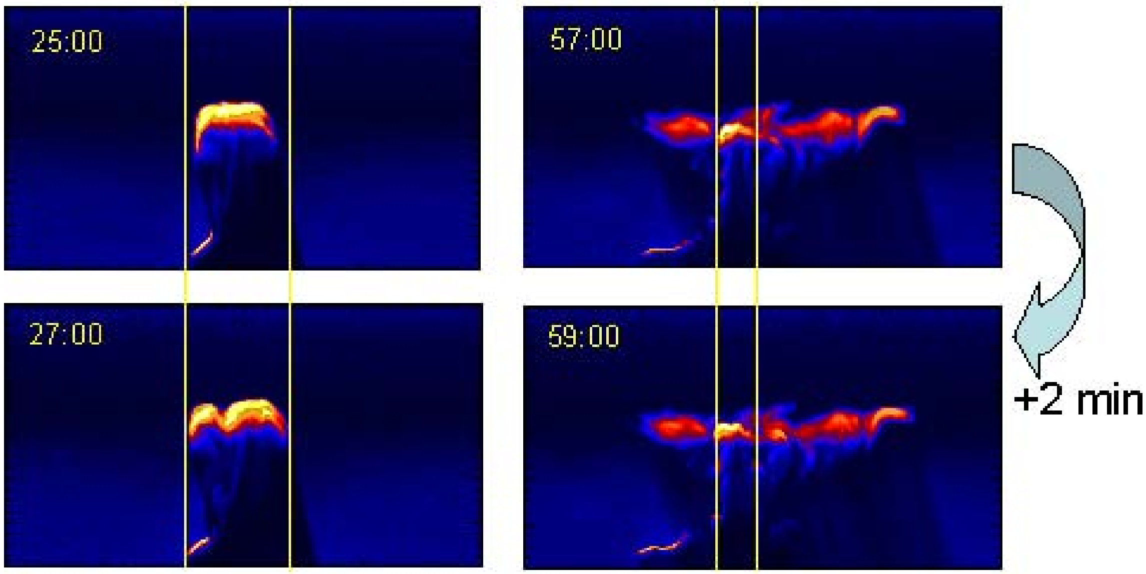

Figure 2. Two minute spread of 3D heating at 25 and 57 minutes into simulation.

Figures 3 and 4 also show the impact of reducing the cost of performing radiative transfer through either altering the spatial or temporal resolution or accuracy of the computation. By reducing the model's spatial resolution (4 km) 3D radiative effects are minimized, and differences in the cloud fields produced by applying 3D or 1D radiation are negligible. If we increase the time step and temporally average the cloud field between the calls to the radiation code the results are similar to those found for reducing the horizontal size of the atmospheric columns. By increasing the time-step (2 min), not averaging, and maintaining constant heating rate between the steps the results are closer to those shown for the reference case. However, this method is physically unappealing since it can apply heating rates computed for a cloud to clear sky and vice versa.

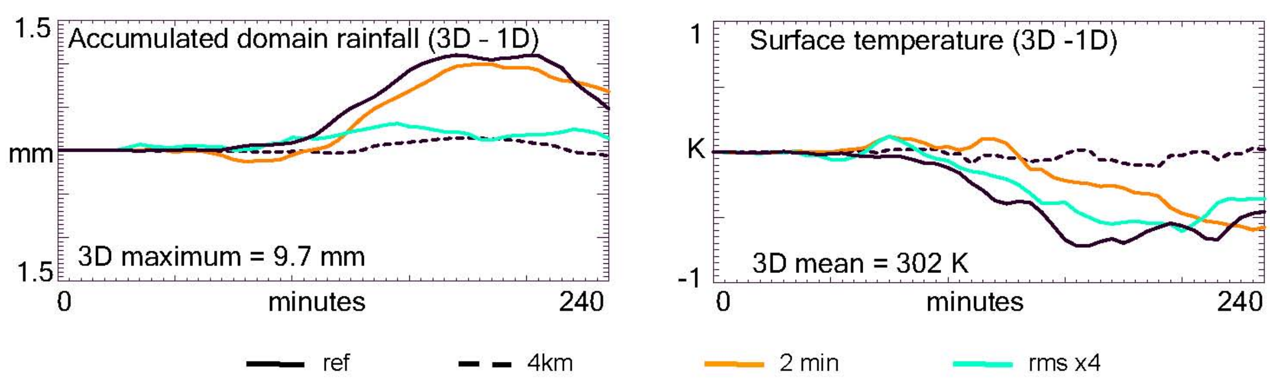

Figure 3. Difference (3D-1D) of accumulated domain rainfall (mm) and domain average surface temperature (K) for reference case (solid), 4 km resolution (dash), 2 minute time-step (gold) and quadrupling of noise (green).

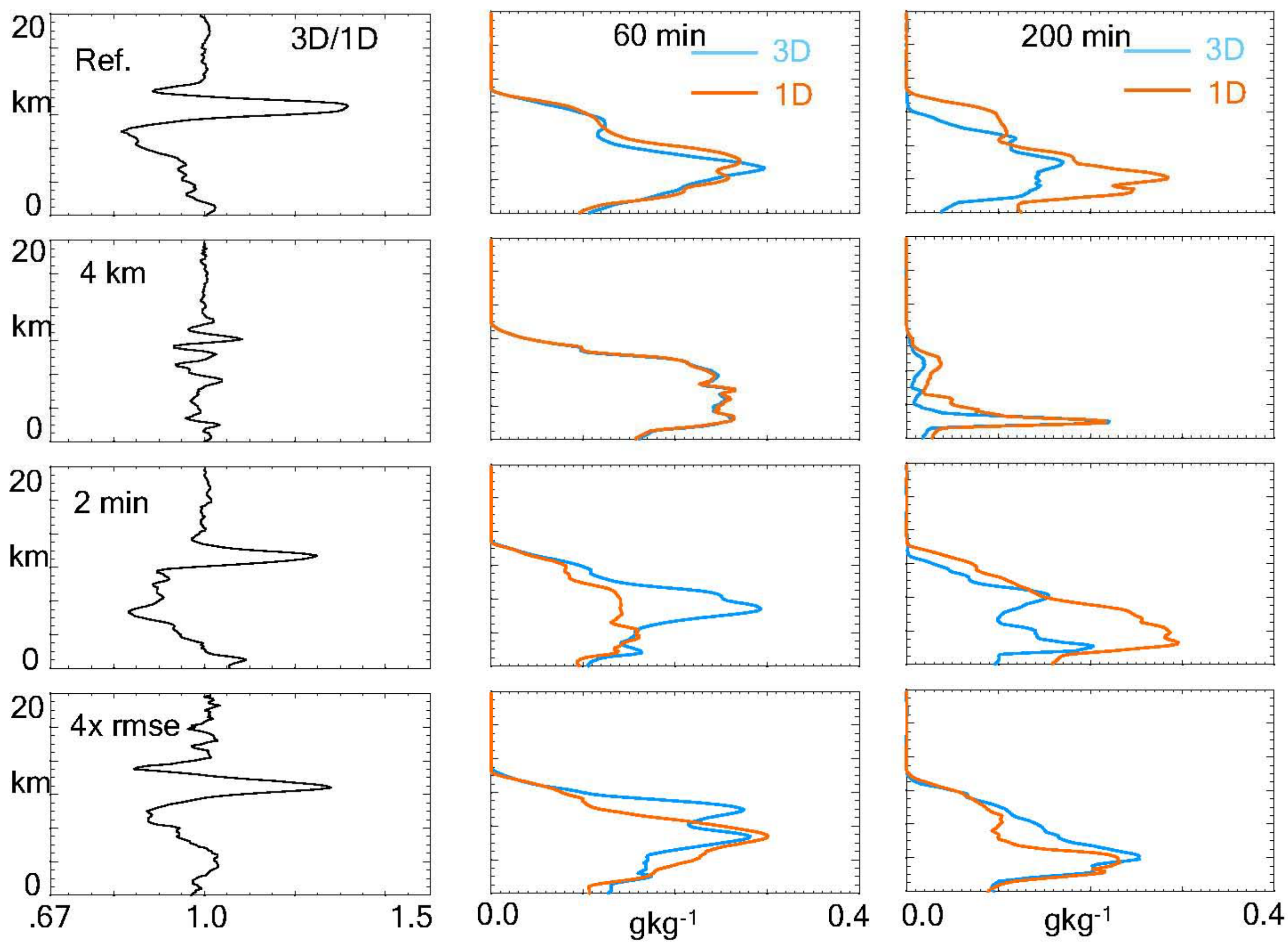

Figure 4. Ratio (3D/1D) of the average heating rate profile (left panel). Cloud condensate profile for 3D (blue) and 1D (gold) at 60 and 200 minutes into simulation (right panel).

Because the radiation is computed using the Monte Carlo method its accuracy is a function of the number of photons processed. Figure 5 shows the column average RMSE for heating rates and surface irradiance. In the atmosphere and at the surface the RMSE is highly variable with areas of low absorption being the least accurate. In regions with high heating rates the accuracy is many times greater. This favorable and expected result reduces the accuracy requirement for the entire domain. However, at some level the noise, in a sense, smoothes the differences between the 1D and 3D radiative fields. Since this noise is injected into the dynamics at each time-step its impact cannot be assessed statistically, but must be determined through a sensitivity analysis. An example of one realization is for a decrease in accuracy by a factor of 4 (RMSE x4). Here, the results are complex with a smoothing process being mixed with what seems to be an introduction of chaotic perturbations into the dynamics.

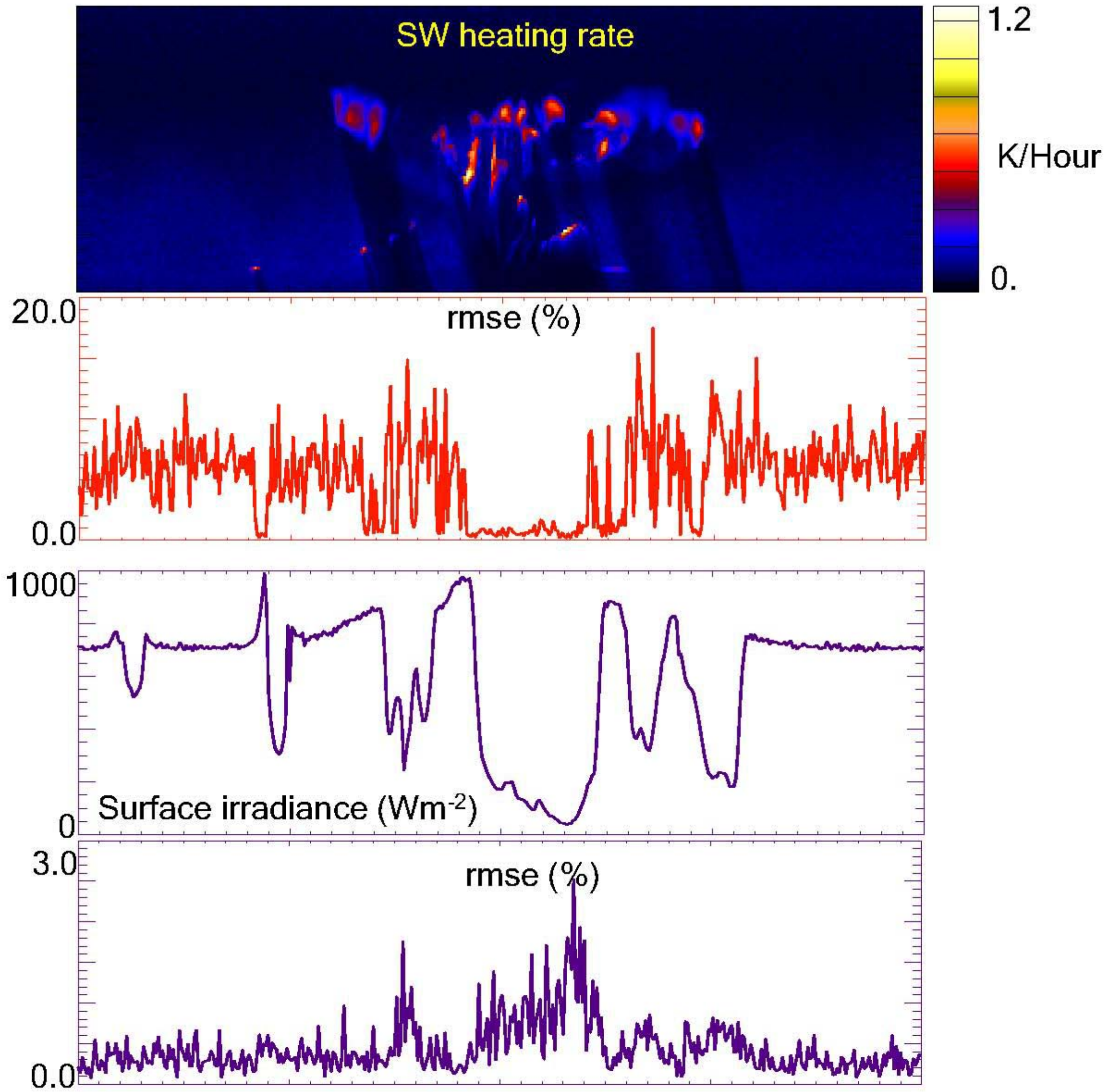

Figure 5. Shortwave heating rate and column average RMSE (upper panels). Surface irradiance and RMSE (lower panels).

The work presented here will be continued to determine the spatial resolution where the impact of 3D radiation effects on cloud field dynamics asymptotes, using this resolution the longest time step possible to maintain a cloud parcel within a column at maximum wind speeds, and the fewest number of photons required to reduce possible chaotic perturbations while preserving fidelity between the 1D and 3D results.

References

O'Hirok, W, P Ricchiazzi, and C Gautier. 2005. "Incorporation of 3D shortwave radiative effects within the weather research and forecasting model." Presented at the Fifteenth ARM Science Team Meeting Proceedings, Daytona Beach, Florida, March 14-18, 2005.

O'Hirok, W, and C Gautier. 2005. "The impact of model resolution on differences between independent column approximation and Monte Carlo estimates of shortwave surface irradiance and atmospheric heating rate." *Journal of the Atmospheric Sciences* 62:2939-2951.