Incorporation of 3D Shortwave Radiative Effects within the Weather Research and Forecasting Model

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Introduction

A principal goal of the Atmospheric Radiation Measurement (ARM) Program is to understand the 3D cloud-radiation problem from scales ranging from the local to the size of global climate model (GCM) grid squares. For climate models using typical cloud overlap schemes, 3D radiative effects are minimal for all but the most complicated cloud fields. However, with the introduction of "superparameterization" methods, where sub-grid cloud processes are accounted for by embedding high resolution 2D cloud system resolving models within a GCM grid cell, the impact of 3D radiative effects on the local scale becomes increasingly relevant (Randall et al. 2003). In a recent study, we examined this issue by comparing the heating rates produced from a 3D and 1D shortwave radiative transfer model for a variety of radar derived cloud fields (O'Hirok and Gautier 2005). As demonstrated in Figure 1, the heating rate differences for a large convective field can be significant where 3D effects produce areas of intense local heating. This finding, however, does not address the more important question of whether 3D radiative effects can alter the dynamics and structure of a cloud field. To investigate that issue we have incorporated a 3D radiative transfer algorithm into the Weather Research and Forecasting (WRF) model. Here, we present very preliminary findings of a comparison between cloud fields generated from a high resolution non-hydrostatic mesoscale numerical weather model using 1D and 3D radiative transfer codes.

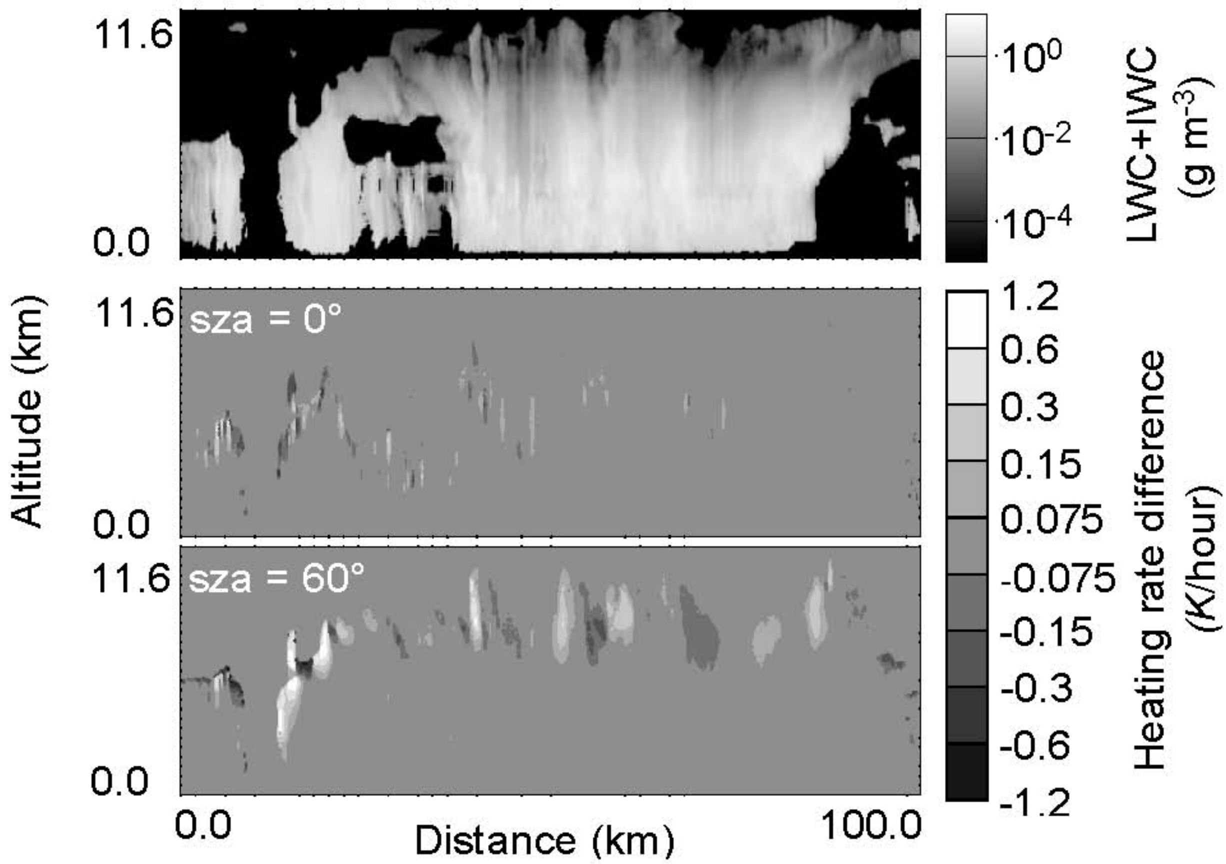

Figure 1. Cloud field derived from millimeter cloud radar (top) and difference in heating rate between 3D and 1D computation (K/hour).

Model Simulations

The 3D shortwave model we have incorporated within the WRF model is based on the Monte Carlo method. Gas (k-distribution), cloud (water and ice) and aerosol optical properties are computed using the shortwave Rapid Radiative Transfer Model (RRTM) for each atmospheric column. Sixteen bands are used to cover the entire solar spectrum. The droplet effective radius is initially set to 10 μm and the ice to 40 μm. To approximate for optical properties of snow, graupel and rain, the mixing ratios and effective radii of the droplets and ice are modified based on the relative concentration and efficiencies of each constituent. The Monte Carlo process is performed on the entire field until the maximum heating occurring within each column has an estimate error of less than 5%. A typical full broadband computation takes approximately 5 min.

Simulations are based on the WRF 2D squall line idealized test case. The field consists of 200 columns and 80 layers having a resolution of 250 m in all directions. The y boundaries are periodic while the x boundaries are open along the direction of the wind field. The wind, temperature and humidity profiles representative of a tropical atmosphere are obtained from the supplied input sounding. A temperature perturbation in the lower center of the field is used to initiate convection. Cloud microphysics (water, ice, graupel, snow and rain) are computed using the Lin at al. scheme. A 1.5 order turbulent kinetic energy (TKE) closure scheme is used for sub-grid turbulence. Since shortwave radiation greatly impacts the heating of the surface, it is important to include surface-air exchanges in the model simulation. The 3D turbulence scheme as initially set in the code does not provide for these exchanges. However, it does remove the vertical diffusion component when a planetary boundary layer (PBL) parameterization is employed to avoid double counting. In this preliminary evaluation the YSU PBL is used for the vertical diffusion, but for more detailed analysis in the future the code will be modified to use a single turbulence method. For the surface layer physics the Monin-Obukhov approach is used along with a 5 layer sub surface thermal diffusion scheme to compute the fluxes required for the air-surface interface. Longwave radiation is computed in 1D using RRTM. In the shortwave, the Monte Carlo model is used for both the 3D and 1D simulations. In the case of the 1D, the horizontal extent of each column for the radiation calculation is set at 1000 km to negate the effects of photon horizontal transport. In this manner, any differences in the simulated cloud fields are directly related to 3D radiative effects. The time step for the dynamics and microphysics is 3 seconds and the radiation and surface physics are computed every 2 min. The simulation starts at 14:00 and is run for 120 min.

The simulated cloud fields (water, ice, graupel, snow and rain) and shortwave heating rates for the 1D and 3D radiation computations are presented in Figure 2. The log of the mixing ratio +1 and log of the heating rates are used to highlight the spatial patterns in the fields. Initially, the 3D radiation field shows more absorb solar radiation on the cloud edge facing the sun and less heating in the atmosphere shadowed by the cloud. The increased heating on the illuminated cloud side retards cloud development while the cooling atmosphere in the shadow raises the relative humidity and enhances cloud development. This differential heating across the cloud gradually tilts the cloud development away from the direction of the sun. Further into the simulation at 72 min., the 3D field shows areas of intense local heating much lower in the cloud field than that occurring for the 1D case (Figure 3). This increase heating lower in the cloud field leads to more complex cloud structure as indicated in the mixing ratios of water vapor and water droplets (Figure 4). Two distinct locations of precipitation are also seen to develop during this period. Over the two hour simulation period the cloud field with 3D radiation produces 10 % more domain average accumulated rainfall than the field simulated using the 1D radiation.

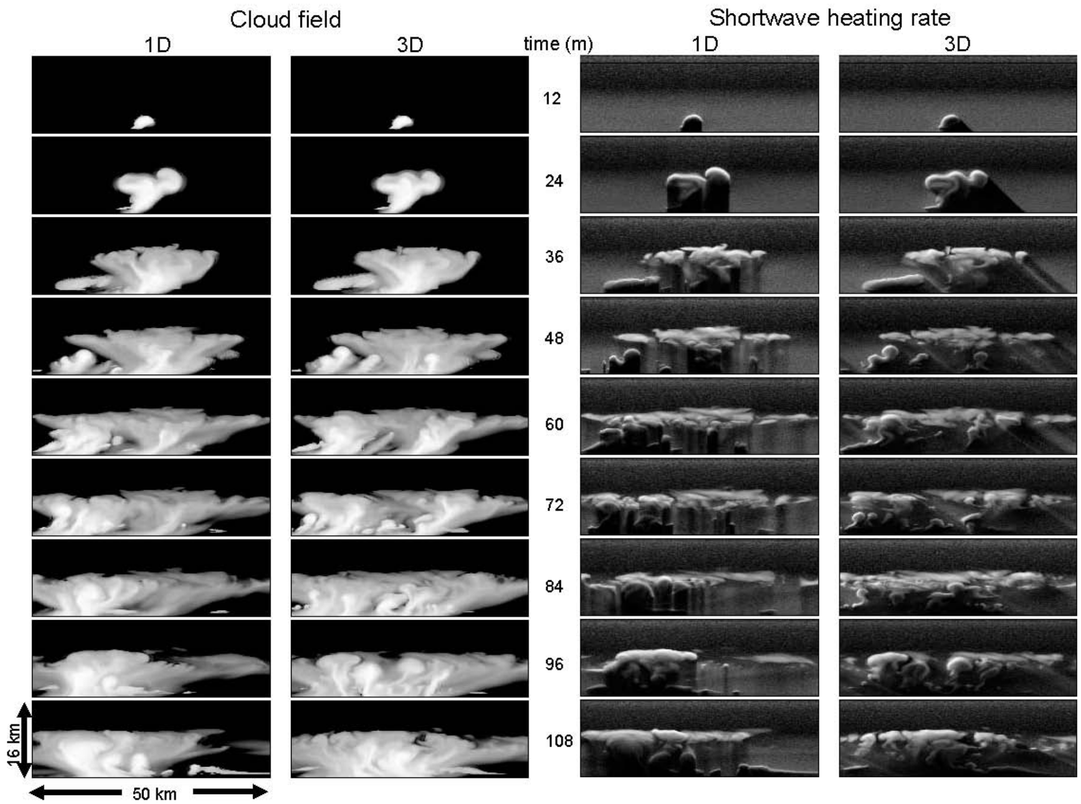

Figure 2. Time sequence of the sum of the cloud droplet, ice, snow, graupel and rain mixing ratios (left panels) and shortwave heating rates (right panels). To make the spatial patterns viewable the dynamic range has been increased by taking the log of the values plus one.

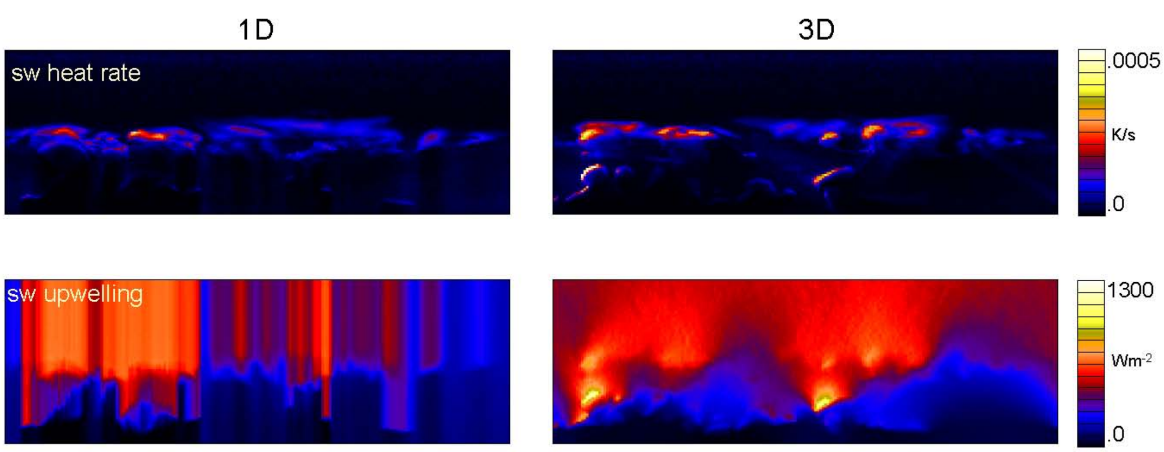

Figure 3. Shortwave heating rate and upwelling flux for 1D and 3D shortwave radiation computations.

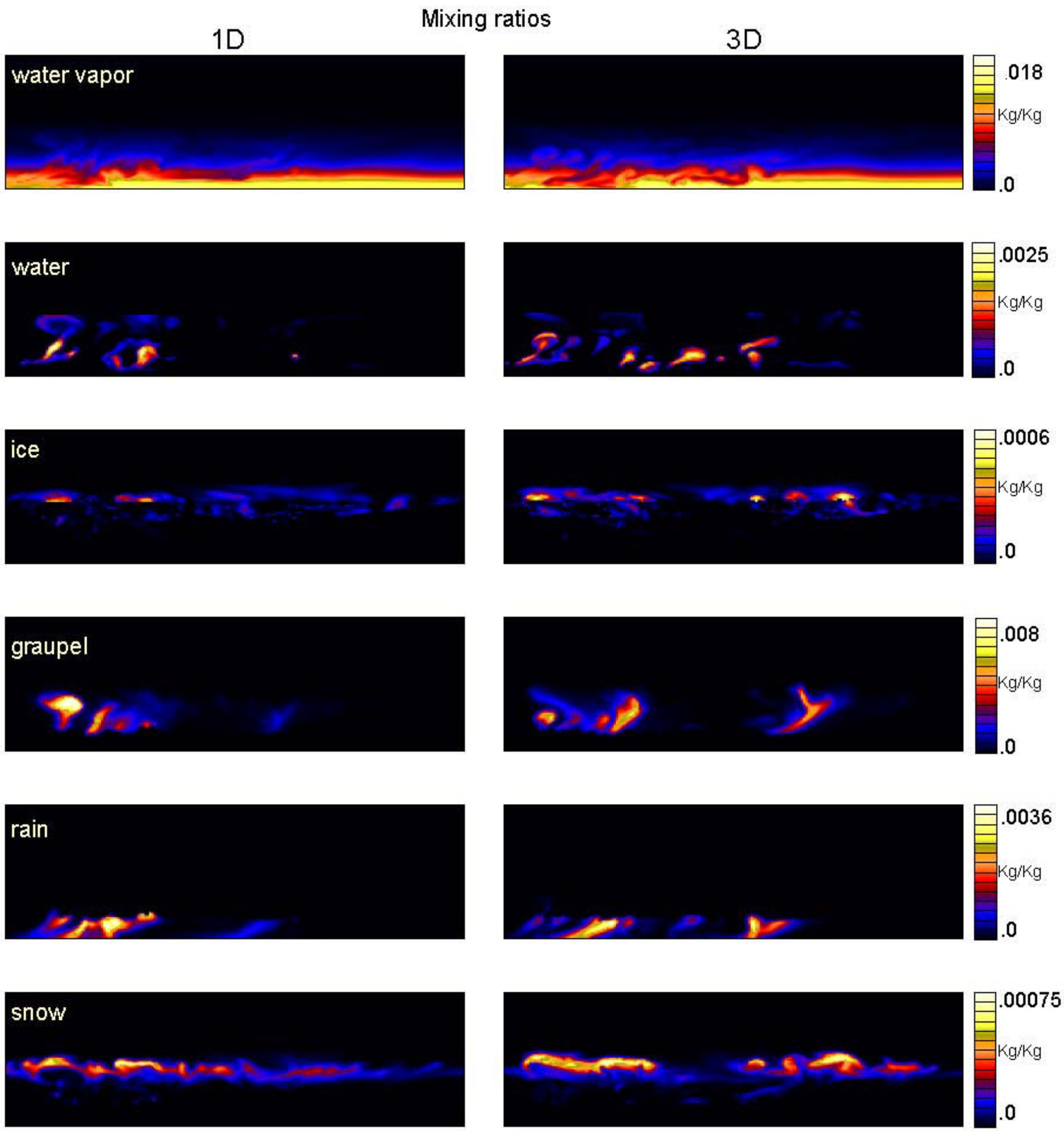

Figure 4. Water vapor, droplet, ice, graupel, rain, and snow mixing ratios 72 min. into the simulation for 1D and 3D shortwave radiation computations.

Conclusion

These initial results show that the impact of 3D radiation on cloud dynamics is not negligible. The inclusion of 3D radiative effects tends to make the cloud field more complex and "energetic." These findings support the need to perform more exacting simulations with the model code adapted to this specific problem. Further investigations will include a large sample of model atmospheres, initial perturbations, and boundary conditions.

References

Randall, D, M Khairoutdinov, A Arakawa, and W Grabowski. 2003. "Breaking the cloud parameterization deadlock." *Bulletin of the American Meteorological Society* 84, 1547–1564.

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