Sensitivity of Cloud Water Optical Path to Explicit Presentation of Hydrometeor Spectra in Detailed Bin Microphysical Scheme in WRF

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1. Introduction

Clouds have large effects on radiative transfer and the heating rates in a cloudy atmosphere. The absorption, reflection, and transmission in the atmosphere due to clouds depend on the droplet spectra. The different size distributions of same water content results in different optical paths. The widely used cloud microphysical schemes are bulk schemes where the cloud droplet sizes and concentrations are implicitly parameterized. Thus, the effects of hydrometeor spectra on radiation are difficult to evaluate. In this study, a detailed bin microphysical scheme is implemented where the cloud droplet sizes are explicitly represented to quantify the spectra effects on radiative transfer.

Effects on shortwave radiation due to clouds include an increase in optical path length of water vapor absorption due to scattering by cloud droplets, and absorption by liquid droplets. Changes in cloud droplet absorption linearly affect the extinction optical thickness, which in turn affects the single-scattering albedo (Cotton and Anthes 1989). The single-scattering albedo varies strongly with droplet size. In clouds with high droplet concentrations and smaller droplet sizes, the single-scattering albedo is much greater. For shortwave radiation, optical thickness can be expressed as a function of drop size distribution and the depth of the cloud or in terms of cloud droplet mixing ratio. Stephens (1978b) also showed that it can be parameterized using liquid water path (LWP) and an effective droplet radius. Optical thickness determines the amount of energy both reflected and absorbed from clouds, so it is important that it is parameterized correctly in cloud models. LWP is very important in influencing cloud absorptance. Differences in droplet concentration affect liquid water content in clouds and hence also affect cloud LWP (Cotton and Anthes 1989).

Optical thickness is even more important for determining the amount of longwave radiation that is absorbed in clouds. However, optical thickness for the longwave spectrum can be parameterized principally as a function of liquid water content of a cloud and does not depend strongly on the cloud droplet spectrum (Cotton and Anthes 1989). Previous research has shown however that cooling rates can differ by a factor of four in the upper regions of clouds for a cloud containing droplets versus one containing precipitation (Wiscombe and Welsch 1986).

Due to the effects of droplet spectra on radiation, an improved parameterization of radiative transfer that includes a detailed description of the droplet spectra could significantly improve numerical model output.

2. Methodology

A detailed microphysics scheme developed by Geresdi (1998) uses the moment-conserving technique to accurately model the evolution of hydrometeor distributions. It uses 36 size bins to describe the evolution of the size distribution for each of the hydrometeor species (Rasmussen 2002). This model was adapted for and implemented into the WRF model. The goal of this study is to use the detailed bin microphysics scheme to improve the parameterizations of radiation by including information on the droplet size distribution. The focus of this study was on warm clouds in order to examine the effects of liquid droplets only. The cases were run using the ideal hill2d simulation. This allows for orographic lift to produce a cloud in the middle of a west-east oriented domain. Because the cloud is produced by orographic lift, it allows for the dynamics of the case to be quiescent.

In the simple shortwave radiation scheme developed by Dudhia (1989), the downward component of the shortwave flux is calculated using layer transmissivity, which includes cloud absorption and cloud albedo. Cloud absorption and cloud albedo are bilinearly interpolated from tabulated functions depending on LWP (Dudhia 1989). Shortwave radiation can be calculated more accurately using effective droplet radius information, explicitly calculated in the detailed bin scheme. Although future changes will be made to the scheme, a sensitivity study was conducted where LWP was changed in the shortwave radiation scheme from its explicit calculation using cloud and vapor mixing ratios to zero. This was changed in order to see the sensitivity of changing the LWP to radiative properties.

Longwave radiation in a cloudy atmosphere can be parameterized according to Stephens (1978b) with effective emmitance as

$$\varepsilon \uparrow\downarrow = 1 - \exp(-a_0 \uparrow\downarrow W),$$

where W is the LWP and $a_0 \uparrow\downarrow$ are the upward and downward emittances. Dudhia (1989) gives the effective absorption coefficient as

$$\propto_p = \frac{1.66}{2000}\left(\frac{\pi N_0}{\rho_r^3}\right)^{\frac{1}{4}} \quad m^2g^{-1},$$

where ρ_r is the particle density and N_0 is the intercept for the Marshall-Palmer size distributions. Although the radiative transfer code in the WRF model obtains the absorption values for rain and snow from this equation (assuming they are constant), work by Feigelson (1970) showed that the absorption coefficient varies strongly with drop size distribution, ranging from 0.002 to 0.17 m^2g^{-1}. In order to see the sensitivity of this, the absorption coefficient of rain was changed in the WRF code from the original value of 0.33E-3 to 1.86E-4, which corresponds to a change in the intercept for the Marshall-Palmer size distributions by a factor of ten.

The path-integrated LWP is used in the rrtm scheme to calculate the optical depth of the cloud. Because the optical depth of the cloud is important in calculating how much longwave radiation is absorbed, an improved calculation of LWP using the bin scheme should help in producing better calculations of longwave radiation parameters. In order to see the sensitivity of the LWP on longwave radiation, the path integrated LWP was changed from its original calculation using rain mixing ratio to zero. Another case was examined where the path integrated LWP was increased from its original value.

Table 1. Brief description of the experiments

Expt	Name	Description
I	Ctrl	Bin scheme, RRTM scheme, Simple Dudhia shortwave scheme
II	Kessler	Bulk (Kessler) microphysics scheme
III	Longwave	Varying LWP and absorption coefficients in RRTM scheme
IV	Shortwave	Varying LWP in simple Dudhia scheme

3. Preliminary Results

The control run used the detailed bin microphysics scheme, the simple Dudhia shortwave radiation scheme, and the rapid radiative transfer model (rrtm) longwave radiation scheme. The simulation time was five hours with cloud development beginning after the first hour. In all of the runs, the cloud developed over the hill, approximately 400 km east of the west edge of the domain. Differences were analyzed at hour five of the simulation when the cloud was fully developed at that time. A case was also examined where the microphysics scheme was changed to the warm cloud scheme developed by Kessler in order to examine the effects of using the detailed scheme produced mixing ratios on longwave and shortwave radiation. The various cases and their descriptions are given in Table 1.

a). Shortwave Radiation

Shortwave downward radiation (SWDOWN), accumulated grid-scale total precipitation (RAINNC), cloud mixing ratio (QC) and temperature (T) difference fields were plotted for the control case versus the case where the liquid water path in the shortwave radiation scheme was set to zero. SWDOWN between the control and changed shortwave scheme case differed by as much as -195 W m^{-2} in the center of the domain (Fig. 1). When the liquid water path was changed to zero in the code the downward shortwave radiation increased. The difference in RAINNC was negligible, temperature differed by more than 0.5 K in some regions of the cloud, and QCLOUD differed by no more than -6E-5 kg kg^{-1} between the two cases.

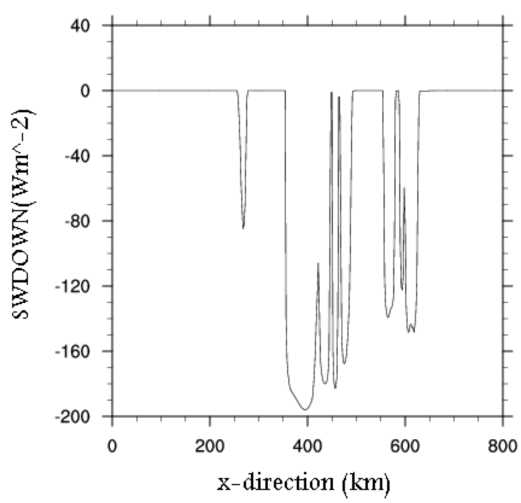

Fig. 1 Difference in downward shortwave radiative flux between the control and perturbed case.

b). Longwave Radiation

The outgoing longwave radiation (OLR), ground longwave radiation (GLW), accumulated gridscale total precipitation (RAINNC), cloud mixing ratio (QC) and temperature (T) difference fields were all plotted for the control case versus each of the longwave sensitivity cases.

The different microphysics schemes (bin versus Kessler) produced the largest differences

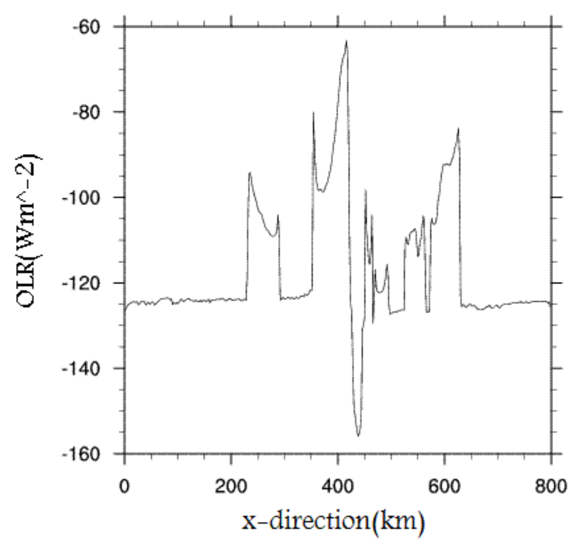

Fig.2. Difference between outgoing longwave radiation between the control case and the case with the bulk Kessler microphysics

in all of the above mentioned fields. GLW between the control detailed scheme and Kessler scheme differed from 20 to 165 W m^{-2} across the domain, OLR differed from -150 to -65 W m^{-2} (Fig. 2), RAINNC differed at a maximum of 8 mm in the center of the domain, and QC differed at a maximum of 8E-4 kg kg^{-1} in the center of the cloud.

The differences between the control case and the cases with changes to the radiation scheme were largest over the area where the cloud was present in the center of the domain. The differences between the control case and the

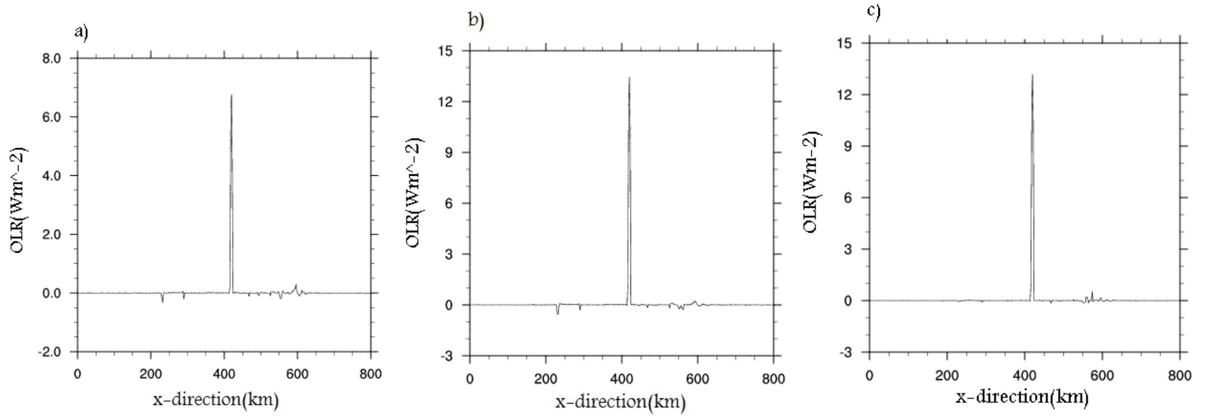

Fig. 3 Difference in outgoing longwave radiation between the control case and a) the modified absorption coefficient case b) the case where PLWP is reduced to zero and c) the case where PLWP is increased.

case with the change in absorption coefficient was around 12 W m^{-2} over the cloud for GLW, 7 W m^{-2} over the cloud for OLR (Fig. 3a), and negligible for RAINNC. Changes in cloud mixing ratio and temperature were negligible for all areas of the cloud.

The discrepancies between the control case and the case with the reduced path integrated LWP were also small with the largest change in GLW around 20 W m^{-2}, 13 W m^{-2} for OLR (Fig. 3b), and negligible for most other variables. The differences between the control case and the case with the increased LWP were around 19 W m^{-2} for GLW, 13 W m^{-2} for OLR (Fig. 3c).

In general, the changes to the longwave radiation scheme had small differences from the control run in comparison with the differences when the Kessler microphysics scheme was used as well as in comparison with the differences when the shortwave radiation scheme was changed.

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