P491.A **A PARAMETERIZATION OF CLOUD MICROPHYSICS AND FRACTIONAL CLOUDINESS FOR NWP AND CLIMATE MODELS**

Laura D. Fowler*
CIRA, Colorado State University, Fort Collins, Colorado

1. INTRODUCTION

Parameterizing the horizontal extent of cloudiness in regional- to global-scale numerical weather prediction and climate models in a physically-based and consistent manner with cloud water and ice condensates remains a difficult challenge. Recent cloud parameterizations that were developed for global- and meso-scale climate and weather forecast models have focused on the inclusion of detailed prognostic cloud microphysics processes, but assume that a cloud occupies the entire model grid-cell (Morrison and Gettelman 2008; Thompson 2008). While this assumption remains valid at cloud-resolving scales, it rapidly breaks down as the horizontal resolution of the computational domain decreases. More importantly, this assumption yields significant biases in the calculation of precipitation evaporation (Jakob and Klein 2000).

We have developed a prognostic parameterization of bulk cloud microphysics and fractional cloudiness in Version 3 of the Advanced Weather Research Forecast (ARW) model. Our objectives aim at studying the impact of horizontal discretization on simulating the lifetimes of large-scale cloud systems, and seamlessly representing cloud microphysics processes at all spatial scales. This scheme is based on the work of Fowler et al. (1996), but also includes the following enhancements:

- A prognostic stratiform cloudiness, similar to that of Tiedtke (1993);
- Separate thermodynamic properties for the cloudy and cloud-free fractions of the model grid-cell;
- Fully consistent interactions with convection, as it affects cloud condensates and cloud amount, and;
- Distinct vertical velocities for the cloudy and cloud-free fractions of each grid cell, formulated in such a way that stratiform clouds remain neutrally buoyant through time.

In sections 2 , we provide a short description of the cloud scheme and its implementation in ARW. Early results of a 18-hour experiment over the eastern US are described in section 3. Conclusions and future work are outlined in section 4.

2. DESCRIPTION OF PROGNOSTIC SCHEME

The mathematical framework of the stratiform cloud parameterization is described in great details in Randall and Fowler (1999). It is based on the assumption that a model grid-cell of area, A, can be divided into three sub-regions: a cloud-free sub-region of horizontal area A_{clr}, a stratiform-cloudy sub-region filled with stratiform clouds of area A_{cld}, and a convective-cloudy sub-region covered with convective clouds of horizontal area A_{cu}, as seen in Fig. 1. Of course, A is equal to

$$A = A_{cld} + A_{clr} + A_{cld}. \qquad [1]$$

Following Margolin et al. (1997), we allow each sub-region to exchange mass laterally with each of the other two sub-regions inside the grid-cell under consideration. In addition, we allow each sub-region to exchange mass with the neighboring grid cells.

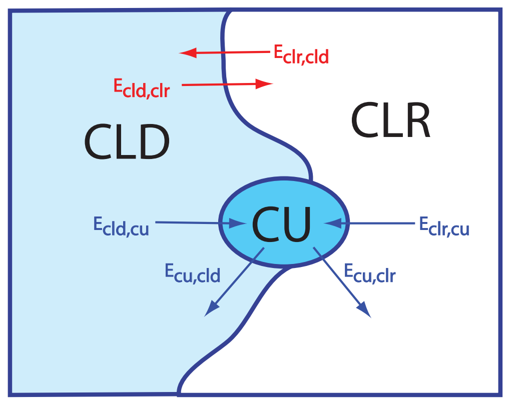

Figure 1: Illustration of the mass exchange between the cloud-free (CLR), stratiform-cloudy (CLD), and convective (CU) fractions of the model grid-box.

Let q_c be the in-cloud cloud water mixing ratio in the *CLD* fraction of a grid-cell. The prognostic equation for q_c can be expressed as

$$\begin{aligned}\frac{\partial}{\partial t}\left(mA_{cld}q_c\right) &= -E_{cld,clr}q_c - \frac{A_{cld}}{A}E\,q_c + Dq_{cu} \\ &+ A_{cld}\left(S_{cld}\right) - \frac{\partial}{\partial z}\left\{\left(A_{cld}\overline{M} + AM_{meso}\right)q_c\right\} \\ &+ \frac{\partial}{\partial z}\left(A_{cld}M_c q_c\right) + \sum_i F^i_{cld}q_c.\end{aligned} \qquad [2]$$

The prognostic equation for the cloud fraction A_{cld} is the continuity equation for Eq. [2]. It is obtained by setting q_c equal to 1 and the source term S_{cld} equal to zero, or

* *Corresponding author address*: Laura D. Fowler, CIRA, Colorado State University, Fort Collins, CO 80523-1375. E-mail: fowler@cira.colostate.edu

$$\frac{\partial}{\partial t}\left(mA_{cld}\right)=-E_{cld,clr}+E_{clr,cld}-\frac{A_{cld}}{A}E+D$$
$$-\frac{\partial}{\partial z}\left\{\left(A_{cld}\overline{M}+AM_{meso}\right)\right\} \qquad [3]$$
$$+\frac{\partial}{\partial z}\left(A_{cld}M_c\right)+\sum_i F_{cld}^i.$$

In Eqs. [2]-[3], m is the mass of dry air. $E_{cld,clr}$ and $E_{clr,cld}$ are the mass exchange rates from the *CLD* to the *CLR* fractions of the model grid-cell, and from the *CLR* to the *CLD* fractions of the model grid-box, respectively. E and D are rates of entrainment and detrainment in and out of the convective fraction (*CU*) of the model grid-box. S_{cld} is the source or sink of q_c to cloud microphysics processes or other physics processes, for instance diffusion. q_{cu} is the cloud water mixing ratio inside convective updrafts.

$E_{cld,clr}$ and $E_{clr,cld}$ are parameterized as functions of the evaporation and condensation rates in the stratiform cloudy fraction of the model grid-box, or

$$E_{clr,cld}=C_{clr,cld}mA\left[\frac{A_{cld}\left(1-A_{cld}\right)}{A^2}\right] \qquad [4]$$
$$\times\left(\frac{\dot{q}_{c,cond}+\dot{q}_{i,cond}}{q_c+q_i}\right),$$

and

$$E_{cld,clr}=-C_{cld,clr}mA\left[\frac{A_{cld}\left(1-A_{cld}\right)}{A^2}\right] \qquad [5]$$
$$\times\left(\frac{\dot{q}_{c,evap}+\dot{q}_{i,evap}}{q_c+q_i}\right).$$

In Eqs. [4]-[5], $C_{cld,clr}$ and $C_{clr,clr}$ are constant parameters, and q_i is the cloud ice mixing ratio. $\dot{q}_{c,evap}$ and $\dot{q}_{c,cond}$ are evaporation and condensation rates. in the stratiform-cloudy fraction of the model grid-cell. Finally, M, M_{meso}, and M_c are the large-scale, meso-scale, and convective mass fluxes. The parameterization of M_{meso} which results because of the temperature difference between the *CLD* and *CLR* fractions of the grid-box is described in great details in Randall and Fowler (1999), and omitted here for brevity. The last terms on the right-hand side of Eqs. [2] and [3] represent exchange mass terms between the *CLD*, *CLR* fractions of the model grid-cell under consideration and its neighboring grid-cells.

In order to solve the mass and temperature budgets for the entire model grid-box, we write equations similar to Eq.[2] for each individual water species (cloud water, cloud ice, rain, snow), and water vapor and temperature in the *CLD* fraction of the grid-box. We also solve similar budget equations for the corresponding grid-mean water species, and water vapor and temperature. Differences between cloudy and cloud-free water vapor, rain, and snow, and temperature are determined diagnostically.

Details on the implementation of the cloud scheme, the parameterization of precipitation, and modifications made to the ARW dynamical core can be found in Fowler (2010).

3. EARLY RESULTS

The cloud microphysics scheme has been tested at different horizontal scales. We illustrate the performance of the scheme by describing the results of a 30-km run over the eastern continental US. WRF was initialized for January 24th 2000 (12:00Z) with ETA-212 analysis data. Boundary conditions were updated every 6-hours using ETA-212 analysis data. The experiment ran for 18 hours.

Using the accumulated total precipitation to quantify horizontal extent and intensity, Fig. 2 shows the growth of a precipitating cloud system along the eastern US. On January 24th (17:00Z), a cloud system is shown to form along the Atlantic coast of Florida and inland. By the end of January 25th (17:00Z), the precipitating cloud system is shown to cover most of the eastern US coast.

Figure 3 shows cross-sections of non-falling (cloud water/ice) and falling (rain/snow) condensates across a south-north axis of the cloud system. Figure 4 is like Fig. 4, but along a west-east axis. Both cross-sections depict the largest total cloud water/ice mixing ratios (shaded) between 600 and 700 hPa. Cloud fractions exceed 80% throughout most clouds, in conjunction not only with the largest non-falling condensates but also with largest ice mixing ratios closer to cloud-tops (~300 hPa). Several clouds on the edge of the main cloud system exhibit low cloud water/ice mixing ratios associated with fractional cloudiness greater than 60%. Figures 3 and 4 highlight the increased falling of rain and snow below both cloud water/ice maxima for all deepest clouds. In addition, Fig. 4 shows rain/snow falling below clouds and reaching the ground prior to completely evaporating.

Finally, Figs. 5 and 6 display the spatial distribution of the 850 hPa cloud water mixing ratio and horizontal cloud fraction for January 24th 2000, averaged between 17:00Z and 18:00Z. Figure 5 is the output of a run with a 10-km horizontal resolution while Fig.6 is the output of a 30-km horizontal resolution. As expected, details in the distribution of the cloud water mixing ratio and fractional cloud fraction are washed out as the spatial resolution is decreased. Both figures show large areas of thin clouds. The cloud parameterization appears to work consistently between the two horizontal resolutions.

4. CONCLUSIONS

We have successfully developed a set of prognostic equations that consistently describe the time and space variations of cloud condensates and horizontal area that they occupy in the model grid-cell. Single-moment cloud microphysics processes are as described in Fowler and Randall (1996), and the cloud fraction is prognosed as a function of condensation and evaporation rates.

Because the microphysics scheme is fully implicit, it can be used at horizontal resolutions commonly used in global numerical weather prediction and climate models, and at cloud-scales. One chief objective in implementing a prognostic equation of fractional cloudiness in ARW was to provide a parameterization of cloud microphysics processes that could be used for a wide range of spatial horizontal scales since ARW was itself designed to run at multiple scales. Initial results indicate that the scheme is performing well for short-term experiments. Further work is needed to validate the scheme, not only against cloud microphysics parameterizations available in WRF, but also against observations.

5. REFERENCES

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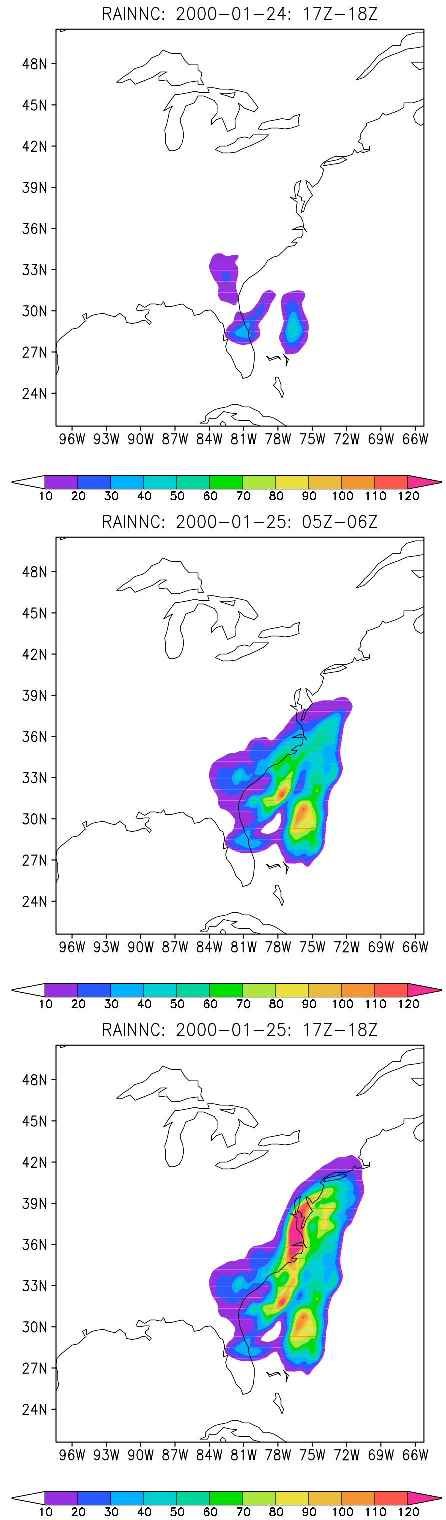

Figure 2: Spatial distribution of the accumulated large-scale precipitation for January 24th 2000 averaged between 17:00Z and 18:00Z (top panel), January 25th 2000 averaged between 05:00Z and 06:00Z (middle panel), and for January 25th 2000 averaged between 17:00Z and 18:00Z (bottom panel). Units are mm.

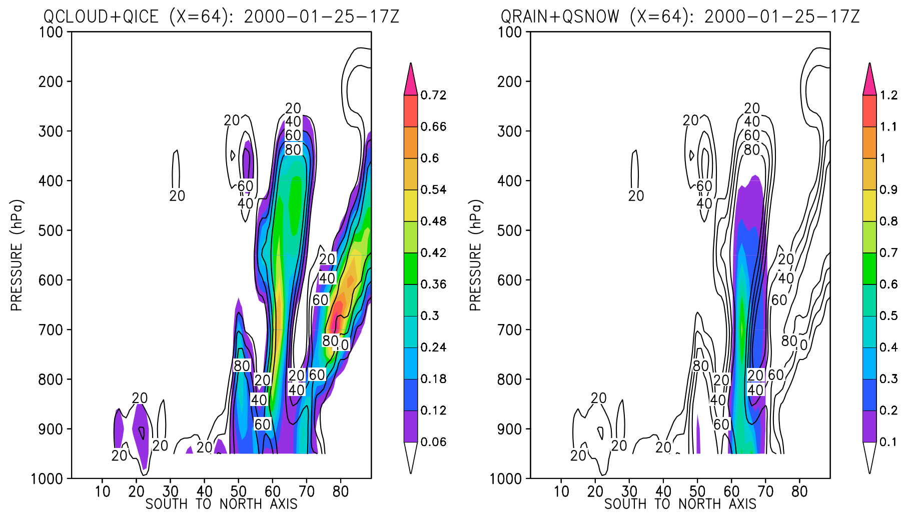

Figure 3: Cross-sections of the cloud water plus ice mixing ratio (shaded; left panel) and rain plus snow mixing ratio (shaded; right panel) and cloud fraction (contour) along a south-north axis through the cloud system, for January 25th 2000 at 17:00Z. Units are g kg^{-1} for mixing ratio and % for cloud fraction.

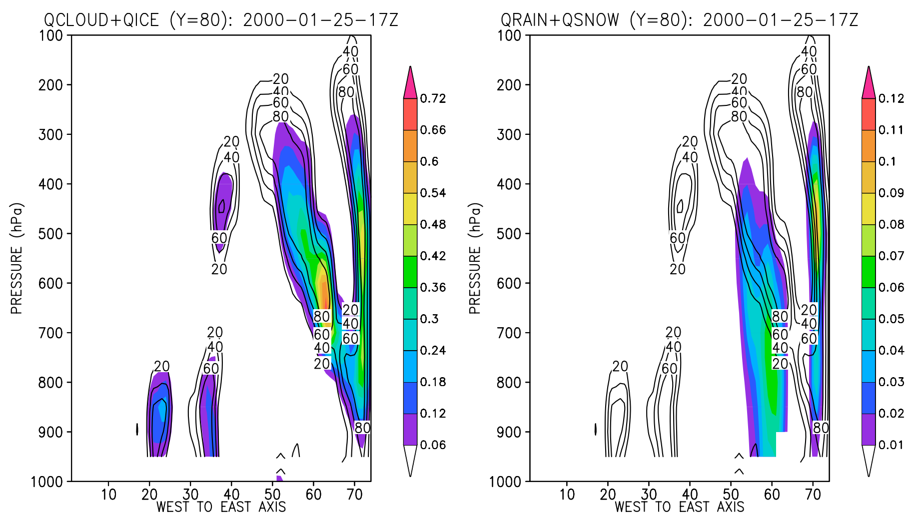

Figure 4: As Fig 3, but for a west-east cross section through the same cloud system, for January 25th 2000 at 17:00Z.

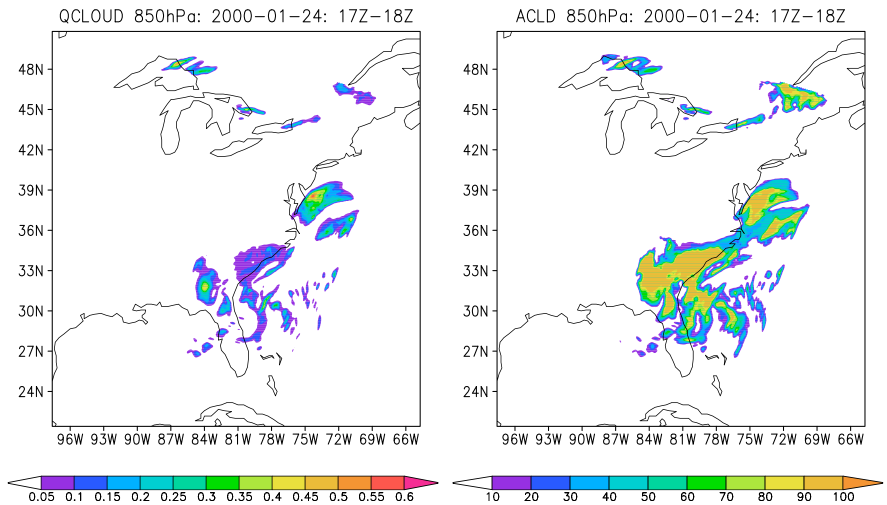

Figure 5: Geographical distribution of the 850 hPa cloud water mixing ratio (left panel) and cloud fraction (right panel) for the experiment with a 10-km horizontal distribution. Units are g kg^{-1} for the cloud water mixing ratio, and % for the cloud fraction.

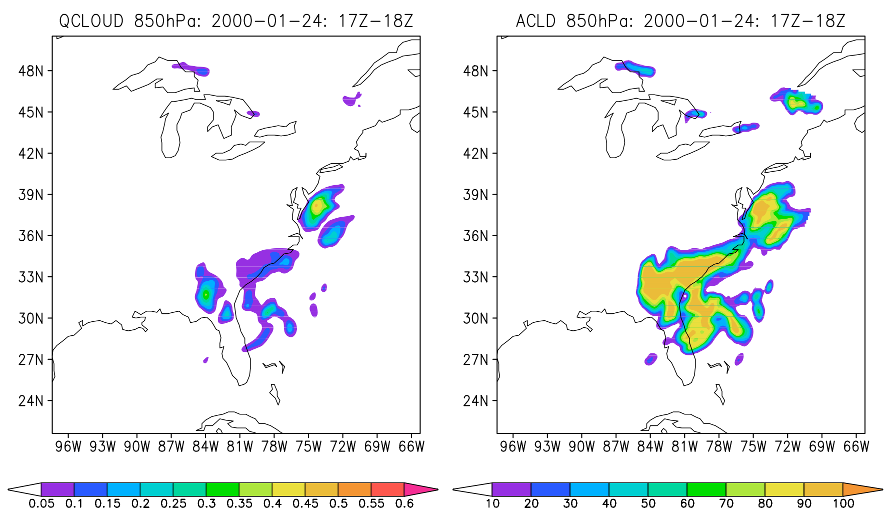

Figure 6: As Figure 5, but for the experiment with a 30-km horizontal resolution.