The Use of Partial Cloudiness in a Bulk Cloud Microphysics Scheme: Concept and 2D Results

SO-YOUNG KIM AND SONG-YOU HONG
Korea Institute of Atmospheric Prediction Systems, Seoul, South Korea

(Manuscript received 11 August 2017, in final form 23 May 2018)

ABSTRACT

The source and sink terms of microphysical processes vary nonlinearly with cloud condensate amount. Therefore, partial cloudiness is one of the important factors to be considered in a cloud microphysics scheme given that in-cloud condensate amount depends on the cloud fraction of the grid box. An alternative concept to represent the partial cloudiness effect on the microphysical processes of a bulk microphysics scheme is proposed. Based on the statistical relationship between cloud condensate and cloudiness, all hydrometeors in the microphysical processes are treated after converting them to in-cloud values by dividing the amount by estimated cloudiness and multiplying it after the computation of all microphysics terms. The underlying assumption is that all the microphysical processes occur in a cloudy part of the grid box. In a 2D idealized storm case, the Weather Research and Forecasting (WRF) single-moment 5-class (WSM5) microphysics scheme with the proposed approach increases the amount of snow and rain through enhanced autoconversion/accretion and increases precipitation reaching the surface.

1. Introduction

The correct representation of cloudiness in atmospheric models is essential for the realistic treatment of cloud–radiation feedback. Cloudiness can be estimated by the diagnostic approach as a function of relative humidity (e.g., Slingo 1987) or both relative humidity and cloud water (e.g., Xu and Randall 1996). Prognostic cloud fraction schemes (e.g., Tiedtke 1993; Wilson et al. 2008) represent various sources and sinks of cloudiness, which are relatively complex and presumably physically robust (e.g., Klein and Jakob 1999; Delanoe et al. 2011). The source and sink terms in a prognostic scheme include planetary boundary layer (PBL) mixing, convection, advection, condensation, and evaporation. To address the uncertainty in the source and sink terms of deep convection processes, Park et al. (2016) proposed a revised prognostic cloud fraction scheme through a direct linkage between hydrometeors in the cumulus parameterization scheme (CPS) and cloud fraction. These efforts have mainly focused on the realistic treatment of cloud–radiation feedback, especially for long-term simulations, which are seasonal or beyond.

For large-scale precipitation physics, the bulk parameterization of hydrometeors, primarily based on the works of Lin et al. (1983) and Rutledge and Hobbs (1983), has been a central feature in the representation of cloud and precipitation processes in both general circulation models and mesoscale models (e.g., Tao and Simpson 1993; Forbes et al. 2011). Since then, there have been continuous efforts to improve the realism of the microphysics scheme by adding the number concentration of hydrometeors (e.g., Ferrier 1994; Seifert and Beheng 2001; Milbrandt and Yau 2005; Morrison et al. 2005; Thompson et al. 2008; Lim and Hong 2010) or by introducing spectral bin microphysics (e.g., Lynn et al. 2005). As the parameterization of the effects of partial cloudiness and cloud vertical overlap was earlier popular for radiation in general circulation models and global weather prediction models (e.g., Tiedtke 1993; Xu and Randall 1996), the partial cloudiness concept has also been included in the microphysical processes in global atmospheric models. For example, the critical relative humidity less than unity, which is a factor to make condensation occur in a subsaturated grid box if grid-mean relative humidity is greater than this critical value, has been used to calculate microphysics terms such as the condensation process (e.g., Smith 1990; Rotstayn 1997; Zhao and Carr 1997; Wilson et al. 2008;
Molod 2012). Given that the source and sink terms of the microphysical processes vary nonlinearly with cloud condensate amount, partial cloudiness is an important factor to be considered in a microphysics scheme.

Meanwhile, there have been efforts to include partial cloudiness effects more explicitly in computing microphysical processes (e.g., Bechtold et al. 1993; Jakob and Klein 2000; Chosson et al. 2014). Bechtold et al. (1993) proposed the use of partial cloudiness in warm-rain microphysics and demonstrated that the correct coupling of a partial cloudiness scheme and a microphysics scheme improves the actual cloudiness and precipitation fields by enhancing autoconversion and lowering the evaporation rate. Jakob and Klein (2000) also investigated the effects of cloud and precipitation overlap by separating the cloudy and clear portions of the grid cell, where the precipitation flux is represented by the average value in both areas. They also showed a reduction in precipitation evaporation and an increase in accretion rate. Chosson et al. (2014) applied a similar concept to a two-moment microphysics scheme and argued that the subgrid cloud and precipitation fraction technique can be used across model resolutions.

The abovementioned methods use the amount of cloud condensates (precipitation hydrometeors) divided by cloud fraction (precipitation fraction) for the calculation of microphysical processes, and this kind of concept has been partly or fully adopted in bulk microphysics schemes of some current models. For example, the Integrated Forecasting System (IFS) treats the microphysical processes separately within and outside the cloud (Forbes et al. 2011), and consequently, in-cloud condensate amount is used for several processes such as autoconversion of cloud water and ice. In the Application of Research to Operations at Mesoscale (AROME) model (Seity et al. 2011), the in-cloud value is used for the calculation of autoconversion of cloud water to rain. Chosson et al. (2014) has implemented their method for all microphysical processes in a two-moment bulk microphysics scheme of the Global Environmental Multiscale (GEM) model, and a similar approach has been adopted in a two-moment bulk microphysics scheme (Morrison and Gettelman 2008) of the Community Earth System Model (CESM). The Met Office Unified Model (UM), furthermore, considers change of cloud fraction due to the microphysical processes such as sublimation, melting, and falling of the ice (Wilson et al. 2008). In the Weather Research and Forecasting (WRF) Model, on the other hand, partial cloudiness is not taken into account in cloud microphysics schemes.

In this study, we propose an alternative method of using partial cloudiness in the microphysics parameterization scheme (MPS) for large-scale precipitation physics. The basic assumption is that all the microphysical processes in the MPS are treated with properties estimated for the cloudy portion of the grid box, in which cloudiness with the cloud water or ice in computing source and sink terms of microphysics is unity, whereas the prognostic hydrometeors are grid-mean values elsewhere. The amount of hydrometeors in the MPS can be computed based on the statistical relationship between condensed cloud water and cloudiness estimated from a satellite observation. The proposed method is implemented in the WRF single-moment 5-class (WSM5) microphysics scheme (Hong et al. 2004) and evaluated in a 2D idealized storm case of the WRF Model.

The following section will present the background and concept of this study. Section 3 will describe the experimental setup and discuss the results. The concluding remarks will be given in the final section.

2. Partial cloudiness in MPS

a. Background and concept

Pioneered by Bechtold et al. (1993), the vertical distribution of partial cloudiness and the use of environmental and in-cloud values for thermodynamic variables clarify the uncertainties of falling precipitation in association with cloud vertical overlapping issues. This approach is further elaborated by Jakob and Klein (2000) and Chosson et al. (2014) for practical use. There are two major issues in this approach. First, the cloudiness used in the MPS in their studies considers all existing clouds including the source from CPS. Thus, it is questionable to apply the same cloudiness value that is used to consider vertical overlapping of clouds for radiation feedback to the microphysics of the MPS. Another issue is that the precipitation flux in the study by Jakob and Klein (2000) is diagnosed without its time tendency. Thus, it might be possible to apply the vertically varying cloudiness to microphysical processes in order to represent the net flux in a realistic way when precipitation substances are diagnosed. However, the sedimentation and dynamical processes of hydrometeors could be treated in a grid-mean property as far as precipitation hydrometeors are prognostic variables.

Considering the abovementioned issues, we propose an alternative concept of partial cloudiness in the MPS. Assuming that all microphysical processes in the MPS should occur on the in-cloud part with the cloud fraction at unity, the grid-mean values of hydrometeors are converted to the in-cloud values before computing microphysical terms and converted back to the grid-mean values. The transfer rates of moisture and heat due to microphysical processes that are calculated within the cloud are also converted to the grid-mean values by multiplication with cloud fraction. This approach is
simple since the vertical overlapping of clouds and the location of clouds in the previous literature are not necessary to be taken into account. The schematic in Fig. 1 shows that microphysical processes are treated with in-cloud values. It is expected that the magnitude of the transfer rate of moisture and heat could be increased as a result of an increase in the amount of hydrometeors in computing source and sink terms. However, the response would not be linear since the in-cloud property influences all microphysical behaviors and the transfer rates are converted to grid-mean rates. The schematic also shows that sedimentation and dynamical processes are treated with grid-mean values. The proposed method aims to represent the microphysical processes more realistically in existing clouds, not for cloud formation.

The cloud fraction $C$ of Park et al. (2016) was adopted in this study (right panel in Fig. 1). If cloud water and cloud ice mixing ratios are separately predicted, Eqs. (5a)–(5c) in Park et al. (2016) can be rewritten as

$$C = \frac{1}{(100 - 50)} \left[ (100 - L_x) C_{\text{max}} + (L_x - 50) C_{\text{min}} \right],$$

where

$$C_{\text{max}} = 5.77 \left( \frac{0.92}{0.96} q^c_{1.07} + \frac{1}{0.96} q^i_{1.07} \right),$$

and

$$C_{\text{min}} = 4.82 \left( \frac{0.92}{0.96} q^c_{0.94} + \frac{1}{0.96} q^i_{0.94} \right).$$

Here, $L_x$ indicates the horizontal grid spacing (km) and $q_c$ and $q_i$ are cloud water and cloud ice contents (g kg$^{-1}$), respectively. Even though this formula is derived based on satellite observations with horizontal resolutions of 50 and 100 km, it is generally available for all resolutions. With this formula, the cloudiness for the cloud content at a level is computed and used in the conversion of hydrometeors between the grid-mean and in-cloud phases.

The above formula provides the unique cloudiness value for given cloud water and ice mixing ratios, without consideration of environmental conditions such as relative humidity. Cloudiness in atmospheric models is usually diagnosed as a function of relative humidity or both relative humidity and cloud condensate amount (e.g., Slingo 1987; Xu and Randall 1996), or it is predicted by more sophisticated schemes consistently reflecting the source and sink by other physical processes (e.g., Tiedtke 1993; Wilson et al. 2008; Watanabe et al. 2009; Park et al. 2016). These diagnostic or prognostic
cloudiness formulas have mainly been utilized in computing radiative fluxes. We note that there is no perfect one-to-one relationship between cloudiness and cloud condensate amount. Although a one-to-one relationship between cloudiness and cloud condensate amount may not be generally applicable to radiation effects, this relationship that is derived from satellite observation data is useful to estimate the cloudiness in computing microphysics terms.

b. Source and sink terms

The effect of using partial cloudiness in microphysical processes was examined using the WSM5 microphysics scheme. In the WSM5 microphysics scheme, accretion rate of cloud water by snow is given by

$$\frac{\partial q_s}{\partial t} = \left( -\frac{\partial q_c}{\partial t} \right)_{\text{accr}} = \pi a_s E_{sc} n_{0s} q_c \left( \frac{\rho_0}{\rho} \right)^{1/2} \frac{\Gamma(3 + b_S)}{\lambda_S^{3+b_S}}, \quad (4)$$

where $q_c$ and $q_s$ are mixing ratios of cloud water and snow, respectively; $a_s$ and $b_S$ are constants for mass-weighted fall speed of snow; $E_{sc}$ is the collection efficiency of cloud water by snow; $n_{0s}$ and $\lambda_S$ are the intercept and slope parameters of the size distribution for snow, respectively; $\rho_0$ is the density of air at a reference state; and $\rho$ is the density of air. Equation (4) is modified to Eq. (5) by including the partial cloudiness effect:

$$\frac{\partial q_s}{\partial t} = \left( -\frac{\partial q_c}{\partial t} \right)_{\text{accr}} = \pi a_s E_{sc} n_{0s} q_c \left( \frac{\rho_0}{\rho} \right)^{1/2} \frac{\Gamma(3 + b_S)}{\lambda_S^{3+b_S}} C. \quad (5)$$

Modified Eq. (5) looks the same as the original one [Eq. (4)] since division of cloud water by the cloud fraction for getting the in-cloud value and multiplication with the cloud fraction for converting to grid-mean rate cancel each other out. However, microphysical rates are not linear to cloud condensate amount. For example, slope parameter of the size distribution for snow is inversely proportional to $q_s^{1/4}$:

$$\lambda_S = \left( \frac{\pi \rho_0 n_{0s}}{\rho q_s} \right)^{1/4}, \quad (6)$$

where $\rho_s$ is the density of snow. Therefore, use of the in-cloud value of snow amount for the slope parameter acts to enhance accretion rates (as shown in Fig. 2a). The accretion rate of cloud water (cloud ice) by rain (snow) also increases by use of partial cloudiness (not shown).

The autoconversion rate of cloud water to rain is given by

$$\left( \frac{\partial q_r}{\partial t} \right)_{\text{auto}} = \left( -\frac{\partial q_c}{\partial t} \right)_{\text{auto}} = \frac{0.104 g E_c \rho_w^{4/3}}{\mu (N_c \rho_w)} \frac{q_c^{7/3}}{C} H\left( q_c - q_{c0} \right) \frac{q_c}{C} C. \quad (7)$$

where $q_r$ is rain mixing ratio, $E_c$ is the mean collection efficiency, $\mu$ is the dynamic viscosity of air, $N_c$ is the number concentration of cloud water (assumed to be $300 \text{ cm}^{-3}$), $\rho_w$ is the density of water, and $H(x)$ is the Heaviside unit step function, which makes the autoconversion process occur only when the cloud water mixing ratio is greater than a critical value $q_{c0}$. Equation (7) is modified to Eq. (8) by including the partial cloudiness effect:

$$\left( \frac{\partial q_r}{\partial t} \right)_{\text{auto}} = \left( -\frac{\partial q_c}{\partial t} \right)_{\text{auto}} = \frac{0.104 g E_c \rho_w^{4/3}}{\mu (N_c \rho_w)} \frac{q_c^{7/3}}{C} H\left( q_c - q_{c0} \right) C. \quad (8)$$

The autoconversion rate is enhanced by considering partial cloudiness (Fig. 2b) because it increases non-linearly with respect to cloud water amount. Also, by using the in-cloud value, the smaller grid-mean value of the cloud water mixing ratio reaches the critical mixing ratio in Eq. (8) rather than in Eq. (7).

Rates of autoconversion of cloud ice to snow, heterogeneous freezing of cloud water, and freezing of rain also increase because of the partial cloudiness effect (not shown). On the other hand, rates of sublimation of snow and melting of snow decrease by considering partial cloudiness (Figs. 2c and 2d). Similarly, ice deposition/sublimation and rain evaporation rates are reduced by considering partial cloudiness (not shown). The effect of partial cloudiness on each microphysical process discussed in this section is a direct effect, in which interactions among microphysical processes are excluded.

3. Numerical simulations

a. Model setup

The WSM5 microphysics scheme is tested on the framework of the Advanced Research version of WRF (ARW) (Skamarock et al. 2008), a community model suitable for both research and forecasting. As in Hong et al. (2004), an idealized 2D thunderstorm experiment is designed to systematically distinguish the intrinsic impact caused by the partial cloudiness in WSM5 by...
virtue of the fixed initial conditions. All other physical processes of shortwave and longwave radiation, cumulus convection, the planetary boundary layer, and the surface layer are turned off. The grid in the \( x \) direction comprised 601 points with a 1-km grid spacing. The number of vertical layers was 80. The model was integrated for 7 h with a time step of 5 s. The initial condition included a warm bubble with radii of 4 km in the horizontal and 1.5 km in the vertical and a maximum perturbation of potential temperature of 3 K at the center of the domain. This experiment served to demonstrate the microphysics in a quasi–steady state that simplifies the interpretation of the results. The control (CTL) experiment is a conventional setup with the cloudiness at unity and the experiment of partial cloudiness in MPS (PCM) employs the MPS with a partial cloudiness effect.

b. Results and discussion

Figure 3 shows the profiles of the domain-averaged hydrometeor mixing ratio from the CTL experiment and their differences between the PCM and CTL experiments, along with the changes in water vapor amount and temperature caused by the inclusion of partial cloudiness. In the CTL experiment, snow is dominant above the freezing level with a maximum amount around 7 km, and there exists more rain than cloud water in the lower troposphere (Fig. 3a). In Fig. 3b, it is apparent that snow amount increases and cloud ice amount is reduced by including the partial cloudiness effect, and the difference for both cloud ice and snow is largest around 7 km, where the amount of snow is a maximum in the CTL experiment. The increase in rain is also distinct. However, there are little changes in cloud water. The partial cloudiness effect increases the amount of water vapor between 7 and 10 km, while drying is induced below 7 km with a maximum change around 1.5 km (Fig. 3c). There is an overall warming effect in the lower and midtroposphere (Fig. 3d). The increase in surface precipitation (Fig. 4) demonstrates that the proposed method enhances the generation of cloud and precipitation, which eventually fall to the ground. These findings are consistent with the results of Bechtold et al. (1993) and Jakob and Klein (2000).
To further elucidate the change in the hydrometeors profile, the budget of microphysical processes and its change by considering the partial cloudiness effect are shown in Fig. 5. While condensation, accretion, evaporation of rain, melting (freezing) of snow (rain), ice deposition, and autoconversion of cloud water to rain are the major processes in moisture transfer, changes caused by the partial cloudiness effect are dominant in condensation, accretion, and ice deposition processes. Vertical profiles of moisture transfer rates were not changed in their shape, but their magnitudes were modulated by the partial cloudiness effect (not shown). It is apparent that the increase in snow amount is largely attributed to the enhanced accretion rate of cloud water by snow, and this is consistent with the analytical comparison result shown in Fig. 2a. The accretion rate of cloud water by rain and the melting rate of snow are also enhanced, which results in the increase in rain amount. Enhanced melting rate of snow by the partial cloudiness effect, which is an opposite response to that in the analytical comparison (Fig. 2d), is likely because of the increased snow amount mainly resulting from the increased accretion rate.

There are little changes in the amounts of cloud water despite the significant increase of the accretion rate of
cloud water by rain and snow. This is because the generation of cloud droplets by condensation also increases. The increased condensation rate by the partial cloudiness effect contributes to drying and warming below 7 km as shown in Fig. 3, and the increase in water vapor amount above 7 km is mainly associated with an enhanced snow sublimation rate and a decreased ice deposition rate. The snow sublimation rate was expected to be reduced by the partial cloudiness effect as shown in Fig. 2c, but it increases in the simulations because the amount of snow itself is larger in the PCM experiment than in the CTL experiment as a result of the enhanced accretion rate. Unexpectedly, the autoconversion rate of cloud water and cloud ice to rain and snow, respectively, slightly decreases because of the partial cloudiness effect. This may be attributed to the smaller amount of cloud water and cloud ice in the PCM experiment than in the CTL experiment, resulting from the increased accretion of both and the decreased deposition of water vapor to cloud ice. More evaporation of rain in the PCM experiment, which also conflicts with the analytical comparison result (not shown), is likely caused by more rain aloft.

4. Concluding remarks

This study proposes a simple method to include the partial cloudiness effect in the MPS. In the proposed method, all microphysical processes are calculated using the in-cloud values of hydrometeors on the assumption that microphysical processes are valid on the cloud scale. After calculating microphysical processes, the transfer rates of moisture and heat are converted to grid-mean values by multiplication with the cloud fraction. Sedimentation processes are treated using the grid-mean values of precipitating hydrometeors, which are all prognostic variables in the scheme considered in this study. As all cloud and precipitation hydrometeors

FIG. 5. Flowchart of microphysical processes and their budget. The transfer rate of moisture for each process in the CTL experiment is shown, and the difference between the PCM and CTL experiments (PCM − CTL) is shown in parentheses (×10⁻⁶g kg⁻¹ s⁻¹). For two-way transfer processes, the dominant process is marked in boldface. The sum of transfer rates for each hydrometeor is written in the box, and its change by the partial cloudiness effect is shown in parentheses.
Delanoe, J., R. J. Hogan, R. M. Forbes, A. Bodas-Salcedo, and Bechtold, P., J. P. Pinty, and P. Mascart, 1993: The use of partial cloudiness effect on the vertical cloud condensate and cloudiness in the MPS, the vertical overlapping of clouds is not taken into account.

By including the partial cloudiness effect, the vertical distribution of hydrometeors is altered. Snow amount increases while cloud ice amount decreases, mainly because of the enhanced accretion rate of cloud droplets and ice crystals by snow. The accretion rate of cloud droplets by raindrops is also enhanced, leading to the increase in rain amount. There were little changes in the amounts of cloud water amount since the reduced cloud water caused by the increased accretion is nearly compensated by the increased generation of cloud droplets by condensation. As the partial cloudiness effect acts to increase the generation of cloud and precipitation hydrometeors, the surface precipitation rate increases overall, which is consistent with previous studies. Reduced ice deposition and increased snow vapor amount in the upper troposphere, whereas drying and warming in the mid- to lower layers are largely attributed to the enhanced condensation rate.

In this study, the effect of partial cloudiness inclusion is investigated in an idealized 2D framework, in which all other physical processes except microphysical processes are turned off to exclusively investigate the intrinsic effect of partial cloudiness in the MPS. In a model with full physics, the response can be different from that shown in this study as changes in hydrometeor profiles could directly alter radiative processes, and this consequently can affect other physical processes such as convection. The evaluation of the proposed method in 3D real-case experiments will be performed in a future study.

Acknowledgments. This work has been carried out through the R&D Project on the development of global numerical weather prediction systems of the Korea Institute of Atmospheric Prediction Systems (KIAPS) funded by the Korea Meteorological Administration (KMA).

REFERENCES


Rutledge, S. A., and P. V. Hobbs, 1983: The mesoscale and microscale structure and organization of clouds and precipitation...


