A modified formulation of fractional stratiform condensation rate in the NCAR Community Atmospheric Model CAM2

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ABSTRACT

This paper describes a modified formulation of stratiform condensation rate associated with fractional cloudiness in the Community Atmospheric Model Version 2 (CAM2). It introduces an equation to link cloudiness change with the variation of total condensate. Together with a diagnostic cloud relationship that represents subgrid scale variability of relative humidity, a closed system is formed to calculate the fractional condensation rate. As a result, the new formulation eliminates the two closure assumptions in the Rasch and Kristjansson [1998] prognostic cloud scheme. It also extends the Sundqvist [1978] scheme by including the influence of convective detrainment and advection of condensates on the fractional cloudiness.

Comparison is made between the present formulation and the Rasch and Kristjansson scheme by using data from the Atmospheric Radiation Measurement Program (ARM) and through global model simulations with the NCAR CAM2. It is shown that relative to the Rasch and Kristjansson [1998] scheme, the new formulation produces less clouds and a slightly warmer troposphere, thus reducing the original cold bias in the NCAR Community Climate Model (CCM). Even though the overall impact of the new formulation on the model climate is small, the modifications lead to more consistent treatments of fractional cloudiness change, condensation rate, and cloud water change in the model.

1. Introduction

Parameterization of clouds in climate models has been the subject of active research in the last twenty years [Sundqvist, 1978; Slingo, 1987; Le Treut and Li, 1988; Smith, 1990; Ghan and Easter, 1992; Tiedtke, 1993; Del Genio et al., 1996; Fowler and Randall, 1996; Rasch and Kristjansson, 1998]. This is primarily motivated by the importance of potential cloud radiative feedbacks on climate change [e.g., Sommerville and Remer, 1984; Cess et al., 1990; Mitchell and Ingram, 1992]. It is widely recognized that uncertainties in cloud parameterizations are still the main cause of discrepancies in the 1.5 to 4.5 degree global warming simulated in general circulation models (GCM) from a doubling of CO2 concentration in the atmosphere [Cubasch et al., 2001].

Two lines of complication arise in the parameterization of clouds in large-scale models. One is from the spatial and temporal sub-grid scale variability of the dynamic, thermodynamic, and hydrological variables within a GCM grid box. The second is from microphysical processes associated with the size distribution of cloud condensation nuclei and hydrometers. The first aspect is ideally dealt with by using high resolution models, while the second aspect requires spectrally resolved descriptions of cloud particles. The two aspects, unfortunately, interact with each other, and they also interact with the resolved scale atmospheric circulation. Even with the rapid pace of improvement of computing power, it is impossible to resolve the important sub-grid structure and the spectral information of clouds in the foreseeable future for global climate model simulations. As a consequence, simple subgrid scale models and aggregated spectral hydrometer information are still needed to parameterize clouds.

One of the subgrid scale issues of cloud parameterization is the calculation of fractional condensation rate, which is directly related with the calculations of fractional cloudiness and local cloud microphysical processes. In CCM2, condensation rate is calculated based on grid-scale saturation, and temperature and water vapor mixing ratio are correspondingly updated. Fractional cloudiness and cloud water were diagnosed separately from the condensation rate. As a result, time variation of cloud water may be inconsistent with the condensation rate. Later versions of the CCM3 used the Rasch and Kristjansson [1998, hereafter referred to as RK98] prognostic cloud scheme, in which condensation rate is used to update the temperature, water vapor, and cloud water. The condensation rate, however, is calculated based on two closure assumptions, and cloudiness change is not directly linked with cloud water change. Because of these assumptions, the in-cloud condensate, which is diagnosed from the updated cloudiness and the total cloud water, is not constrained and may not be consistent with the cloud water equation for the cloudy portion of the grid box. The line of prognostic cloud schemes following Sundqvist [1978] used one closure assumption to calculate the fractional condensation rate, which is then used to update temperature, water vapor, cloudiness, and total cloud water. Similarly, the in-cloud condensate is diagnosed without considering its own controlling equation.

The present study reformulates the RK98 scheme to start from an in-cloud condensate equation. Total cloud water variation is then expressed in terms of changes of cloudiness and in-cloud condensate. Together with a diagnostic cloud relationship, a closed set of equations is formed to derive the fractional condensate rate. As a result, our formulation eliminates the two closure assumptions used in RK98 and the one closure assumption used in S78 This modification of linking cloudiness change with cloud water also allows the inclusion of cloud water advection and detrainment in the calculation of fractional cloudiness.

The paper starts with the description of the proposed formulation and its implementation in the NCAR CAM. Comparison is made in Section 3 with other schemes. Section 4 first shows results from diagnostic and single column model calculations using field observations from the Atmospheric Radiation Measurement program (ARM) and then results from GCM simulations. The last section summarizes the findings.

2. The formulation

a. governing equations

As in S78 and RK98, the controlling equations of water vapor mixing ratio, temperature, and total cloud water, are written as

$$\frac{\partial q}{\partial t} = A_q - Q + E_r \qquad (1)$$

$$\frac{\partial T}{\partial t} = A_T + \frac{L}{C_p}(Q - E_r) \qquad (2)$$

$$\frac{\partial l}{\partial t} = A_l + Q - R_l \quad (3)$$

where A_q, A_T, and A_l are tendencies of water vapor, temperature, and cloud water from processes other than large-scale condensation and evaporation of cloud and rain water. A_q, A_T and A_l include advective, expansion, radiative, turbulent, and convective tendencies, which may consist of evaporation of convective cloud and convective rain water. For simplicity, we call them advective tendencies. They are considered to be uniformly applied to the whole model grid cell (the assumption of uniform A_T can be relaxed as will be shown in section 2.d). Q is the grid-averaged net stratiform condensation of cloud water (condensation minus evaporation). This definition differs slightly from RK98 who used it for condensation only; it also differs from S78 who used it to include evaporation from both cloud water and rain/snow water. The reason for this distinction will become clear later. E_r is the grid-averaged evaporation rate of rain/snow water. R_l is the conversion rate of cloud water to rain/snow water.

Similar to S78, the controlling equation of relative humidity of U, when written on a pressure surface, can be derived from (1) and (2) as

$$\frac{\partial U}{\partial t} = \alpha A_q - \beta A_T - \gamma (Q - E_r) \quad (4)$$

where

$$\alpha = \frac{1}{q_s}, \quad \beta = \frac{q}{q_s^2}\frac{\partial q_s}{\partial T}, \quad \gamma = \alpha + \frac{L}{C_p}\beta$$

α, β, and γ are all positive. They can be viewed as efficiencies of moisture advection, cold advection, and net evaporation in changing the relative humidity U, thus potentially the fractional cloud cover. As in S78 and RK98, ice saturation is not separately considered here; rather, it is approximated by a weighted average of the saturation mixing ratios over ice and water.

All the above equations are applicable on both grid scale and sub-grid scale as long as Q, E_r and R_l are correspondingly defined. In the following, we use a hat to denote variables in the cloudy portion of a grid box to distinguish them from variables of the whole grid box, and we use a to denote the fractional cloud coverage. For the portion of the grid box that is cloudy before and after the calculation of fractional condensation (i.e., the cloudy area that does not experience clear-cloudy conversion), (4) becomes

$$\alpha\hat{A}_q - \hat{\beta}\hat{A}_T - \hat{\gamma}\hat{Q} = 0 .$$

Thus, the condensation rate in this portion of the grid box is

$$\hat{Q} = \frac{\alpha\hat{A}_q - \hat{\beta}\hat{A}_T}{\hat{\gamma}} \tag{5}$$

and the in-cloud condensate equation becomes

$$\frac{\partial\hat{l}}{\partial t} = \hat{A}_l + \frac{\alpha\hat{A}_q - \hat{\beta}\hat{A}_T}{\hat{\gamma}} - \hat{R}_l . \tag{6}$$

Since the total cloud water can be written as $l = a\hat{l}$, one has

$$\frac{\partial l}{\partial t} = a\frac{\partial\hat{l}}{\partial t} + \hat{l}^{*}\frac{\partial a}{\partial t} \tag{7}$$

The first term on the right hand side of the above equation represents cloud water change of existing clouds, the second term represents cloud water change associated with expansion and contraction of cloud boundaries. We use $\hat{l}^*$ to denote the mean cloud water of the newly formed or dissipated clouds within a time step, as an attempt to crudely describe some subgrid information of cloud water, since theoretically newly formed or dissipated clouds should have zero cloud water content. Practically, however, because of the finite time step in the integration of the cloud water equation, the second term should not be neglected. In the current implementation, $\hat{l}^*$ is taken as $\hat{l}$.

Substituting the above into (3), using (6), and $R_l = a\hat{R}_l$ as well as $A_T = \hat{A}_T$, $A_q = \hat{A}_q$, $A_l = \hat{A}_l$, one has:

$$\hat{l}^* \frac{\partial a}{\partial t} = (1-a)A_l + Q - a\left(\frac{\alpha A_q - \hat{\beta} A_T}{\hat{\gamma}}\right) \qquad (8)$$

This equation states that the condensation rate is linked with fractional cloudiness change as required by the total water budget. As long as Q can be calculated to integrate equations (1) - (3), it can be also used to integrate (8) to predict cloudiness changes. The definition of Q to include both condensation and evaporation of cloud water is therefore the most convenient in the present formulation. If $\hat{l}^*$ is set to be zero in (8), the condensation rate Q can be directly derived from (8). The scheme then becomes extremely simplified.

Note that we do not have a true prognostic equation for cloudiness as in Tiedtke [1993] and Randall and Fowler [2001]. We therefore cannot explicitly consider advection of cloud volumn and detrainment of cloud mass from convection. Equation (8), however, attempts to describe these processes by using the source of cloud water (A_l) divided by the in-cloud water. This feature is lacking in the RK98 and S78 schemes. Equation (8) is not integrated in the present formulation. Instead, it is used to calculate the condensation rate described as follow.

b. Sub-grid scale assumption

Following RK98, we use the CCM diagnostic fractional cloud scheme as our sub-grid scale assumption. Namely, the grid-scale relative humidity and fractional cloud cover are related as

$$a = a(U, b) \qquad (9)$$

where *b* denotes a generic variable describing vertical stability, local Rechardson number, cumulus mass flux etc. *b* changes with space and time. This equation is assumed to be valid when the relative humidity *U* is larger than a threshold value U_{00}, which is the minimum grid-scale relative humidity with clouds.

Taking partial derivative of the above equation with respect to time, one has

$$\frac{\partial a}{\partial t} = \frac{\partial a}{\partial U}\frac{\partial U}{\partial t} + (\frac{\partial a}{\partial b})\frac{\partial b}{\partial t} \qquad (10)$$

We now define

$$F(a) = \frac{\partial a}{\partial U} \text{ , and } F(b) = [(\frac{\partial a}{\partial b})/(\frac{\partial a}{\partial U})]\frac{\partial b}{\partial t}$$

and assume that $F(b)$ can be calculated without the knowledge of cloudiness change or the condensation rate. Substituting the relative humidity equation (4) into the above equation, one has

$$F^{-1}(a)\frac{\partial a}{\partial t} = \alpha A_q - \beta A_T - \gamma(Q - E_r) + F(b) \qquad (11)$$

Eliminating $\frac{\partial a}{\partial t}$ between (8) and (11), one can derive

$$Q = c_q A_q - c_T A_T - c_l A_l + c_r E_r + \sigma \hat{l}^* F(b) \qquad (12)$$

with

$$c_q = \frac{\alpha}{\hat{\gamma}} a + (1 - \frac{\gamma}{\hat{\gamma}} a)\sigma\alpha\hat{l}^*$$

$$c_T = \frac{\hat{\beta}}{\hat{\gamma}} a + (1 - \frac{\gamma}{\hat{\gamma}}\frac{\hat{\beta}}{\beta} a)\sigma\beta\hat{l}^*$$

$$c_l = (1 - a)\sigma F^{-1}(a)$$

$$c_r = \sigma\gamma\hat{l}^*$$

where

$$\sigma = \frac{1}{F^{-1}(a) + \gamma\hat{l}^*}$$

All coefficient variables are non-dimensional except for C_T and β with a unit of 1/K. All are positive. Once Q is obtained, (1)-(3) and (8) can be integrated. In practice, (9) can be used to update cloudiness.

Physical interpretation of (12), which is valid when $U \geq U_{00}$, is as follows: moist advection (positive A_q) and cold advection (negative A_T) produce condensation. Evaporation of rain/snow water (positive E_r) also produces cloud condensation, because it changes the mean relative humidity, thus increasing cloud amount and cloud water. Import of cloud water (positive A_l) leads to evaporation. This is less intuitive: it increases cloud fraction, thus requiring a higher clear-sky relative humidity, which has to be generated by evaporation. The increase of cloud fraction from a non-water source through $F(b)$, however, requires condensation.

The prognostic cloud equation can be written as

$$[F^{-1}(a) + \gamma \hat{l}^*]\frac{\partial a}{\partial t} = (1 - \frac{\gamma}{\hat{\gamma}} a)\alpha A_q - (1 - \frac{\gamma}{\hat{\gamma}} \frac{\hat{\beta}}{\beta} a)\beta A_T + (1 - a)\gamma A_l + \gamma E_r + F(b) \tag{13}$$

which can be obtained by either substituting (12) into (8) or by eliminating Q between (11) and (8). Moist advection (positive A_q), cold advection (negative A_T), evaporation of rain/snow water (positive E_r), and import of cloud water (positive A_l) all lead to an increase of cloud amount .

We note that the closure to constrain the calculation of Q is not restricted to (10). Suppose one can predict information on the sub-grid scale distribution of T and q with given Q (say gravity waves, convection plumes, or simply linear functional fitting using neighboring grids), or probability distributions of total water and liquid water temperature

[Le Treut and Li, 1988; Smith, 1990], fractional cloud cover can be then derived and used with (8) to constrain the calculation of Q.

In Smith [1990], where a triangular distribution of total water is assumed and its standard deviation is dependent on the grid saturation mixing ratio, he derived an explicit relationship between grid scale fractional cloudiness and mean relative humidity as (Appendix C in Smith [1990]):

$$a = 1 - \left[\frac{3}{\sqrt{2}}\left(\frac{1-U}{1-U_{00}}\right)\right]^{\frac{2}{3}}.$$

In S78, and similarly, in Sundqvist et al. [1989], Del Genio et al. [1996], and Zhao [1997], (9) is assumed to follow $U = aU_s + (1-a)U_0$ where U_s (=1) is the cloudy sky relative humidity and U_0 is the clear sky relative humidity written as a linear function of the total cloud cover $U_0 = (1-a)U_{00} + a$. U_{00} is a constant, taken as 75% in S78. It can be shown that this relationship between U and a can be derived from a top-hat distribution of the total water content within a grid cell.

c. implementation in the NCAR CCM

The diagnostic cloud scheme of Kiehl et al [1996] and RK98 is used as (9). To evaluate $F(a)$, the cloud routine is called twice each time step with relative humidity perturbed by one percent while holding all other variables in the model fixed. Thus,

$$F(a) = \frac{\Delta a}{\Delta U} = \frac{a^* - a}{U^* - U}.$$

We assume that all b variables are fixed in the stratiform condensation calculation, thus $F(b) = 0$. We also assume a top-hat distribution of the cloud water distribution as in S78 and RK97, thus $\hat{l}^* = \hat{l}$. The entire microphysical package of RK98 is used for: (i) the partition of l into cloud liquid and cloud ice with a prescribed temperature dependent factor, (ii) the calculation of cloud-to-rain/snow conversion rate of $R_l = a\hat{R}_l$, which includes cloud liquid water auto-conversion to rain, the collection of cloud water by rain and snow, the auto-conversion of cloud ice to snow, and collection of ice by snow, (iii) the calculation of rain and snow using R_l integrated from above, (iv) evaporation of rain and snow, which is used as E_r.

With equation (12), input variables of the scheme are: $T, q, p, A_T, A_q, A_l, a, l, F(a)$; E_r is diagnostically calculated as a function of these input variables. Output variables are Q, R_l, updated T, q, l, a, and microphysical conversion rates.

The impact of convection on cloud cover can be implemented straightforwardly. Detrainment of cloud water from the Zhang and McFarlane [1995] convection scheme is used as input in the calculation of A_l, so is the impact of convection on A_T and A_q. The detrained cloud water from convection was originally assumed to evaporate in the Zhang and McFarlane scheme. This is also the treatment in the original Arakawa-Schubert scheme [Arakawa and Schubert 1974]. This portion of the water is now made available to the stratiform clouds for possible evaporation and precipitation. A more rigorous treatment will require the sub-grid scale partition of the detrained water and coupled convective-stratiform interactions, a subject pursued in Randall and Fowler [2001]. Note that in RK98, detrainment of cloud water only affects the condensate budget; while in the present formulation, it also affects the cloudiness and stratiform condensation rate.

Because of the finite time step, in the implementation, the calculation is carried out by categorizing each model grid into one of the four scenarios:

(a) whole grid saturation with $U = 1, Q$ calculated from (7);

(b) $1 > U \geq U_{00}, Q$ calculated from (11);

(c) $U < U_{00}$ but $l > 0$, Q calculated as $-l$;

(d) $U < U_{00}$ and $l = 0$, $Q = 0$.

The use of the threshold relative humidity is a result of the assumption of equation (9).

d. an alternative formulation using total water and liquid water temperature

The above derivation assumed uniform temperature tendency of A_T for the cloudy and clear portions of the grid. This assumption can be relaxed if we use total specific humidity (vapor plus condensate) $r = q + l$ and liquid water temperature $T_l = T - (L / C_p) l$ for our formulation. All we need is to assume that the total water tendency of $A_q + A_l$ and temperature is uniform across the grid box.

The governing equations of total water r and liquid water temperature T_l can be written from (1)-(3) as

$$\frac{\partial r}{\partial t} = A_r + E_r - R_l \tag{14}$$

$$\frac{\partial T_l}{\partial t} = A_{T_l} + \frac{L}{C_p}(R_l - E_r) \tag{15}$$

where $A_r = A_q + A_l$ and $A_{T_l} = A_T - \frac{L}{C_p} A_l$. Since the relative humidity is now written as $U = q / q_s = [r - l] / q_s (T_l + Ll / C_p)$, one can write the relative humidity tendency equation as

$$\frac{\partial U}{\partial t} = \alpha \frac{\partial r}{\partial t} - \beta \frac{\partial T_l}{\partial t} - \gamma \frac{\partial l}{\partial t} \tag{16}$$

This is similar to equation (4).

For the cloudy portion of grid, with the left hand side of (16) setting to zero, one has

$$\hat{\gamma} \frac{\partial \hat{l}}{\partial t} = \alpha \frac{\partial \hat{r}}{\partial t} - \hat{\beta} \frac{\partial \hat{T}_l}{\partial t} = \alpha \frac{\partial \hat{r}}{\partial t} - \hat{\beta} \frac{\partial (\hat{T} - L\hat{l} / C_p)}{\partial t}.$$

It can be shown that the tendency of in-cloud condensate from the above equation is the same as in (6). Next, we use $\hat{T} = T$, with $\alpha = \hat{\gamma} - \hat{\beta} L / C_p$, the above equation then becomes

$$\alpha \frac{\partial \hat{l}}{\partial t} = \alpha \frac{\partial \hat{r}}{\partial t} - \hat{\beta} \frac{\partial T}{\partial t} = \alpha \frac{\partial \hat{r}}{\partial t} - \hat{\beta} \frac{\partial (T_l + Ll / C_p)}{\partial t} = \alpha \frac{\partial \hat{r}}{\partial t} - \hat{\beta} \frac{\partial T_l}{\partial t} - \frac{L\hat{\beta}}{C_p} \frac{\partial l}{\partial t}$$

Substituting (7) into the above, one has

$$(1 + a \frac{L\,\hat{\beta}}{C_p \alpha}) \frac{\partial \hat{l}}{\partial t} = \frac{\partial \hat{r}}{\partial t} - \frac{\hat{\beta}}{\alpha} \frac{\partial T_l}{\partial t} - \frac{L\hat{\beta}\,\hat{l}^*}{C_p \alpha} \frac{\partial a}{\partial t}. \tag{17}$$

The advantage of this equation over the corresponding equation of (6) is that it does not contain the temperature tendency for the cloudy portion of the grid box, which may be different from that in the clear portion of the grid in order to maintain neutral buoyancy of the clouds.

If $\hat{l}^*$ is set to be zero, (17) and (7), together with (14) and (15), form a closed set of equations. With $\hat{l}^*$, the system can be closed by substituting (16) into (10), and using (7) to obtain

$$\frac{\partial a}{\partial t} = F(a)[\alpha \frac{\partial r}{\partial t} - \beta \frac{\partial T_l}{\partial t} - \gamma(a \frac{\partial \hat{l}}{\partial t} + \hat{l}^* \frac{\partial a}{\partial t}) + F(b)] \tag{18}$$

Eliminating $\frac{\partial \hat{l}}{\partial t}$ between (17) and (18), with $\frac{\partial \hat{r}}{\partial t} = \frac{\partial r}{\partial t}$,one derives a prognostic equation of cloudiness as

$$[F^{-1}(a) + \gamma \hat{l}^* \delta] \frac{\partial a}{\partial t} = (\alpha - \gamma a \delta) \frac{\partial r}{\partial t} - (\beta - \gamma a \frac{\hat{\beta}}{\alpha}) \frac{\partial T_l}{\partial t} + F(b) \tag{19}$$

where $\delta = (1 + \frac{aL\partial q_s}{C_p \partial T})$. This is equivalent to equation (13). Once $\frac{\partial a}{\partial t}$ is known, $\frac{\partial \hat{l}}{\partial t}$ and $\frac{\partial l}{\partial t}$ can be determined, which can then be used to derive Q from (3).

3. Comparison with other schemes

KR98 used two closure assumptions in its prognostic cloud scheme. The first was to derive the condensation rate for the cloudy part of the grid box. In the present notation, with the pressure tendency term neglected, this is given as (equation 10 in RK98):

$$Q_{cloudy} = a(\frac{\alpha\hat{A}_q - a\beta\hat{A}_T}{\alpha + a\frac{L}{Cp}\beta}) \tag{20}$$

In our formulation, this quantity is derived in (7) as

$$Q_{cloudy} = a\hat{Q} = a(\frac{\alpha\hat{A}_q - \hat{\beta}\hat{A}_T}{\hat{\gamma}}) = a(\frac{\alpha\hat{A}_q - \hat{\beta}\hat{A}_T}{\alpha + \frac{L}{Cp}\hat{\beta}}) \tag{21}$$

The difference between (20) and (21) is between the terms involving β. When *a* is equal to 1, they give the same results. When *a* equals to 0, the values within the parentheses can differ a lot, but since they are multiplied by *a*, the two formula also give the same results. When *a* is fractional, assuming that α is much larger than the β term in the denominators as is the case in the upper troposphere, the values of the denominators in the above equations are similar. Since $\hat{\beta} > a\beta$, a negative A_T is associated with a smaller Q_{cloudy} in (20). Because clouds are typically associated with negative A_T, caused by adiabatic cooling from upward motions, we expect RK98 to give smaller Q than the new formulation.

RK98 used their second closure assumption to derive Q in the clear portion of the grid box, which is associated with the expansion and erosion of clouds. With notation in the current paper, equation (13) in RK98 is written as

$$Q_{clear} = (\frac{\hat{l}}{1 + a\frac{L}{Cp}\frac{\partial q_s}{\partial T}})\frac{\partial a}{\partial t} \tag{22}$$

Note that in RK98, $\frac{\partial a}{\partial t}$ is obtained from a previous time step, rather than from calculation coupled with Q. In the present formulation, this term Q_{clear} is not explicitly calculated, but it can be easily diagnosed as

$$Q_{clear} = Q - a\hat{Q} \tag{23}$$

Rewriting (8) as

$$Q_{clear} = \hat{l}^* \frac{\partial a}{\partial t} - (1-a)A_l \tag{24}$$

one can directly compare it with (22). (24) states that the expansion and erosion of clouds are associated with both the condensation rate and the cloud water source in the clear-sky portion of the grid cell. Cloud can expand or erode simply due to horizontal advection or detrainment of water from convection. Even if A_l =0, (24) differs from (22) in the coefficient of cloud change.

In the formulation of S78 and Sundqvist et al. [1989], a closure equation was intuitively derived by assuming that the effect of the clear-sky portion of A_q and A_T, together with the evaporation of condensate, is balanced by the increase of clear-sky humidity and cloudiness. In the present notation, Equation (3.19) in Sundqvist et al. [1989] is written as

$$(1-a)\frac{\partial q_0}{\partial t} + (\hat{l} + q_s - q_0)\frac{\partial a}{\partial t} = (1-a)(A_q - \frac{\beta}{\alpha}A_T) + E_r \tag{25}$$

where q_0 is the clear-sky mixing ratio, expressed as $q_0 = q_s U_0$ and U_0 is a function of a described before. To make a contrast with the present formulation, we write the total water equation (14) for the cloudy portion of the grid box as

$$\frac{\partial \hat{r}}{\partial t} = \hat{A}_q + \hat{A}_l - \hat{R}_l \tag{26}$$

Substituting the following

$$r = a\hat{r} + (1-a)q_0$$

into (14), and making use of (26), together with $R_l = a\hat{R}_l$, one gets

$$(1-a)\frac{\partial q_0}{\partial t} + (\hat{l} + q_s - q_0)\frac{\partial a}{\partial t} = (1-a)(A_q + A_l) + E_r \tag{27}$$

Comparing this with (25), it is seen that (25) does not include the A_l term, but it contains an extra term of A_T in the total water budget equation.

4. Impact on model results

We first use field measurements from the Atmospheric Radiation Measurement (ARM) program at the Southern Great Plain (SGP) to analyze the differences. We choose the winter Intensive Observation Period (IOP) of 1999 to minimize the impact of convection. Figure 1 shows the time-pressure cross sections of the temperature, water vapor mixing ratio, and the observed cloud frequency at the ARM SGP central facility [Clothiaux et al. 2001]. Figures 2(a) and 2(b) show the advective and expansion tendencies of temperature and water vapor mixing ratio analyzed from the SGP sounding network by using the constrained variational analysis of Zhang et al. [2001]. Negative advective/expansion temperature tendency is generally associated with positive water vapor tendency. Two main events occurred around day 31 and day 38. Even though three synoptic cloud events are seen in Figure 1(c), the first one is associated with little precipitation. Note that the cloud field is from a single station, while the advective tendency fields are analyzed for a domain of about 300 km in radius. Therefore, the observations are shown only to gain insight about the range of scheme differences.

We further estimated the rate of longwave radiative cooling and shortwave heating for this period as shown in Figures 2(c) and 2(d). They are calculated by using the CCM3 radiation code with observed temperature, water vapor and cloud mask profiles in Figure 1. Cloud liquid water and ice water concentrations are estimated by using the CCM3 diagnostic parameterization with the total liquid water path constrained to the ARM microwave radiometer measurements.

Figure 3(a) shows the calculation of the condensational heating rate $\hat{Q}$ of the cloudy portion of the grid by using the above tendencies as input. Figure 3(b) shows the difference between the present scheme and RK98. It is seen that the large-scale condensation is generally systematically larger in the present calculation, by about ten percent. The pattern of the difference distribution can be clearly explained by examining the pattern of the total temperature tendency masked by clear sky shown in Figure 3(c): negative temperature tendency is associated with larger heating rate in the present formulation.

Because we do not have measurements of the vertical distribution of cloud water concentration, we cannot easily evaluate other aspects of the impact of the scheme. We therefore use the NCAR CCM Single Column Model (SCM) [Hack et al. 1998] and force the SCM by using the advective tendencies in Figures 2(a) and 2(b). Figure 4 shows the time averaged vertical profiles of the stratiform condensation rate from using the present scheme and the RK98 scheme. Consistent with the diagnostic calculation, the present scheme gives systematically larger condensational heating rate when there is fractional cloud coverage.

Figure 5(a) shows the simulation of clouds in the SCM with the new formulation. Comparing with observed cloud frequency in Figure 1(c), the first event is completely missed possibly because the SCM does not include hydrometer advection. The other two events are simulated with some success even though the SCM contains large biases in temperature and moisture similar to those shown in Hack and Pedretti [2000] and Xie and Zhang [2000]. Figure 5(b) shows the difference in clouds relative to the simulation by using RK98. As expected, the direct impact of a larger condensation rate is a warmer and drier upper atmosphere and less clouds.

We then use the above diagnostic and SCM results to interpret the impact of the scheme on GCM results. The NCAR CCM3 is integrated for five years by using the new scheme and the RK98 scheme with climatological seasonal SST forcing. The general features of the model simulation using the RK98 are essentially identical to those presented in RK98. Figures 6(a) and (b) show the distribution of simulated cloud amount with the new scheme, and its change relative to the RK98 simulation in the northern winter season. Figures 6(c) and (d) show the corresponding figures in the northern summer. As expected, the new scheme results in an overall reduction in clouds in the middle and upper troposphere.

The reduction in cloudiness corresponds to appreciable changes in cloud radiative forcing (CRF), especially in the longwave. We therefore reduced the auto-conversion of cold cloud ice to snow in the RK98 microphysical package by changing the threshold value of the ice mixing ratio. In RK98, auto-conversion of ice to snow takes place when the ice mixing ratio exceeds a threshold which is a ramp function of temperature with value of $4x10^{-4}$ at $T=0^oC$ and $5x10^{-6}$ at $T=-20^oC$. In the actual implementation within CCM3, the latter was reduced to $4x10^{-6}$. We raised it to $6x10^{-6}$. This tuning is a result of the crude parameterization of the clouds and its microphysics in the model. This resulted in more cloud ice water in the model to offset the reduced cloudiness in making up the radiative budget of the original model. Figures 7 (a) and (b) show the zonally averaged cloud radiative forcing at the top of the atmosphere, separately for longwave and shortwave for the northern winter season. Also plotted is the satellite measurement from the Earth Radiation Budget Experiment (ERBE). Figures 7 (c) and (d) show the corresponding figures for the northern summer season. It is seen that the overall change between simulations using the new scheme and RK98 is negligible, much smaller than the difference between the model results and the measurements.

The zonal averaged climate simulated using the original CCM with RK98 contains an overall cold bias in the upper troposphere relative to the ECMWF reanalysis, as shown in Figure 8(a) for DJF and Figure 8(c) for JJA. This is also true when the NCEP/NCAR reanalysis is used as reference (not shown). Figures 8(b) and (c) show the change of temperature simulated with the new scheme relative to that with RK98. It is seen that the present formulation gives a slight broad warming in the troposphere, toward reducing the original cold bias.   We have performed several other 5-year model runs starting with different initial conditions and this feature remains to be statistically significant.

Other aspects of the simulated model climate are very close to the control simulation by using the RK98 scheme.   As an example, Figure 9 shows the DJF seasonal averaged distribution of precipitation from using the new scheme, the RK98 scheme, and from the Xie and Arkin [1997] analysis. It is seen that difference of precipitation between the schemes is much smaller than those between models and observation. This insensitivity of the model climate to the prognostic cloud scheme is consistent with RK98 who also reported relatively small difference in climate between the prognostic and diagnostic cloud schemes. This is not entirely unexpected since all these simulations used the same subgrid scale assumption (9).   Other aspects of the model simulations are therefore not presented. The merit of the improved formulation, however, is in the physical consistencies of the calculation which would allow us to incorporate more robust subgrid and microphysical physics.

5.   Summary

We have described modifications to the Rasch and Kristjansson [1998] prognostic cloud scheme. The main point is to link the cloudiness change with variation of the total condensate. This is facilitated by the introduction of an in-cloud condensate equation. This link, together with the diagnostic cloud scheme, forms a closure to calculate the fractional condensate rate. As a result, the new formulation eliminates the two closure assumptions in the original model. We have made comparisons of the present formulation with other schemes. Calculation is made relative to RK98 by using ARM measurements and using the NCAR CCM. It was shown that the present scheme gives slightly larger condensational heating, less clouds, and a warmer troposphere.

Much remains to be done to improve the present formulation. The number of hydrometer species should be increased. The same procedure of Section 2 can be used if ice and water clouds are separately considered. Another important aspect is the incorporation of more realistic subgrid scale features to replace the diagnostic cloud relationship of equation (9), in particular, when convection is present.

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Figure Captions

Figure 1. Time-height distribution of measurements from the ARM SGP winter 1999 IOP. (a) Temperature , (b) water vapor mixing ratio, (c) cloud frequency derived at the SGP central facility.

Figure 2. Temperature and water vapor tendencies derived from the ARM SGP winter 1999 IOP. (a) Advective and expansive temperature tendency, (b) Advective water vapor tendency, (c) and (d): Longwave and shortwave radiative cooling/heating rates.

Figure 3. (a) Diagnosed condensational heating for the cloudy portion of the SGP with the new scheme ($\hat{Q}$). (b) Difference between the new scheme and the RK98 scheme. (c) Total temperature tendency from advection, expansion, and radiation.

Figure 4. Stratiform condensation rate from using the new scheme (solid line) and from using the RK98 scheme (dashed line).

Figure 5. (a) Simulated cloud amount in the SCM with the new scheme. (b) Difference in clouds between the new scheme and the RK98 scheme.

Figure 6. (a) Simulated cloud amount in the CCM with the new scheme in DJF. (b) Difference in clouds between the new scheme and the RK98 scheme in DJF.   (c) and (d): Same as (a) and (b) except for JJA.

Figure 7. (a) Longwave cloud radiative forcing at the top of atmosphere in DJF.   (b) Same as (a) but for shortwave.   (c) Same as (a) but for JJA. (d) Shortwave for JJA.

Figure 8. (a) Temperature bias in the CCM simulation using RK98 for DJF relative to ECMWF reanalysis. (b) Temperature difference between the new scheme and RK98 for DJF. (c) and (d): Same as (a) and (b) except for JJA.

Figure 9. Simulated and observed precipitation for the DJF season. (a) New scheme, (b) RK98 scheme, (c) Xie and Arkin analysis.