An Explicit Cloud Predicting Scheme Implemented in the Florida State University Global Spectral Model and Its Impact

By N. Mannoji¹

Department of Meteorology, Florida State University, Tallahassee, Florida 32306, U.S.A.

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Abstract

An explicit cloud predicting scheme is developed for the Florida State University Global Spectral Model (FSU-GSM). Both cloud water and cloud cover are prognostic variables in the scheme, but they are not advected in the current version. Cloud liquid water and cloud ice are distinguished by a prescribed function of temperature. Source terms are considered for convective cloud as well as stratiform cloud. The predicted cloud water content and cloud cover are provided to the radiation scheme.

The model produces reasonable amounts of cloud cover and cloud water. Clouds originating from convection are important for cloud cover and cloud water except for the polar region. In the tropics, clouds originating from convection account for approximately half of the total cloud cover, and the majority of the high cloud coverage. They also produce half of the cloud water in the mid-latitudes, and are an essential source of the cloud water in the tropics.

The outgoing longwave radiation in the tropics is improved by the explicit scheme, because the scheme includes the clouds originating from the convection. High clouds from convection are essential in the tropics, and have a large influence on the outgoing longwave radiation.

1. Introduction

Diagnostic cloud schemes are widely used in large-scale models including the FSU-GSM (Florida State University Global Spectral Model). Cloud cover is diagnosed by using empirical relationships with the relative humidity in many schemes, *e.g.*, Smagorinsky (1960), Slingo (1987), Saito and Baba (1988). Vertical velocity, static stability and convective precipitation rate can be useful parameters besides relative humidity, as Slingo (1987) shows. This diagnosed cloud cover is used in the model radiation scheme.

Cloud cover, however, is not the only parameter to determine the radiative properties of a cloud. These properties depend on the water content, the phase of the water and the distribution of water droplet or ice particle sizes. A cloud radiation scheme by Stephens (1978) used cloud water content as a parameter. Slingo (1987) demonstrated the importance of cloud water content in the global model. She showed that the well-defined observed minima of OLR (Outgoing Longwave Radiation) in the tropics are clearly lacking in the model when the liquid water content is

based on the saturation water vapour mixing ratio, which is highly dependent on temperature. If the model liquid water content is replaced by values dependent on cloud type and height, the model OLR is improved markedly.

In addition to problems in the radiative properties, diagnostic schemes do not represent the interaction between clouds and the hydrological cycle of the model. The diagnosed cloud cover provided for the radiation scheme has no relation with the condensation calculated by the models for a diagnostic cloud scheme. Though precipitation rate by cumulus convection is a parameter in the Slingo (1987) scheme, only cloud cover is related to the condensation. Coupling the cloud and the condensation is a more consistent method.

Representing cloud water explicitly in a model is a reasonable way not only to determine the radiative properties of clouds on a more physical basis, but also to couple the hydrological cycle with the cloud radiation scheme. Several schemes have been presented to predict cloud in large-scale models. Some of them are not fully interactive with the rest of the model, and some of them do not take the convective cloud into account. Sundqvist (1978) first developed a cloud water prediction scheme, although the cloud cover is diagnosed from relative humidity. Roeck-

¹ Present affiliation: Numerical Prediction Division, Japan Meteorological Agency
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ner *et al.* (1990) and Pudykiewicz *et al.* (1992) present this scheme in a global model and a regional model, respectively. Le Treut (1990), Le Treut and Li (1991) and Smith (1990) make use of "total water", which is the summation of vapour and cloud water. Total water is divided into vapour and cloud water, and cloud cover is diagnosed by using a consistent methodology. A parameterization of cloud radiative properties is not included in Smith (1990). The Lee *et al.* (1992) scheme has more complex processes in the microphysics. Their focus is on the role of radiative heating and ice phase processes in the formation of large-scale clouds. Their model, however, does not predict the wind fields, which are prescribed by another global model. The cloud can change the environmental temperature, but does not interact with wind field. The cloud cover is not predicted but diagnosed by the Smagorinsky (1960) formula. Tiedtke (1991, 1993) predicts both the cloud water content and cloud cover of cumulus cloud and anvil cloud in a consistent way with the cloud mass flux scheme in the ECMWF model. Ose (1993) also developed a scheme to predict cloud water content in the UCLA-GCM, making use of detrainment from cumulus calculated by the Arakawa-Schubert cumulus parameterization. Cloud cover is considered to be equal to 1 or 0.

This paper will describe an explicit cloud predicting scheme implemented in the FSU-GSM. Section 2 contains a brief outline of FSU-GSM with a diagnostic cloud scheme. The explicit cloud predicting scheme is described in Section 3. Section 4 presents results from the model. Finally, a summary and the concluding remarks are given in Section 5.

2. A brief outline of the standard FSU-GSM

We will mention the features of the FSU-GSM only relevant for the present study. The other features are summarized in Krishnamurti *et al.* (1991) and the references therein. The triangular truncation 42-wave (T42), 14-level version of FSU-GSM is used for this research.

The radiation scheme and cloud-cover diagnosis of the model are described in Weiner (1990). The standard FSU-GSM determines cloud cover diagnostically. Cloud cover, C , of three layers, high, middle and low, is expressed by Eq. (1), if RH_m exceeds a critical value, RH_c .

$$C = \left(\frac{RH_m - RH_c}{1 - RH_c} \right)^2. \quad (1)$$

RH_m is the mean relative humidity in the layers, and RH_c is prescribed and listed in Table 1. The sigma levels of high, middle and low layers are also listed there. It is assumed that the cloud top is at the sigma level of 0.141, 0.245, 0.346 in the tropics, mid-latitudes and high latitudes, respectively. Total

Table 1. Sigma levels and critical relative humidity used in the diagnostic scheme.

	Sigma level			RH_c
	20°N–20°S	20°N–60°N 20°S–60°S	60°N–90°N 60°S–90°S	
High	0.141	0.245	0.346	0.4
	0.245			0.4
	0.346			0.4
Middle	0.447			0.5
	0.548			0.5
	0.648			0.5
Low	0.748			0.66
	0.825			0.66
	0.875			0.66

cloud cover is calculated assuming the random overlap of three layers. Optical depth and emissivity of the cloud are functions of temperature and cloud pressure thickness, based on Platt and Harshvardhan (1988).

Moisture is predicted in the lower 11 levels of the 14 levels in the model. The moisture variable is not carried in the levels higher than $\sigma = 0.2$. The water vapour amount in those upper levels used by the radiation scheme is extrapolated from the value at the uppermost level predicted. The condensation is produced by an adjustment scheme and a modified Kuo scheme (Krishnamurti *et al.*, 1983).

3. Scheme

3.1 Basic equations for cloud water and cloud cover

Both the cloud water mixing ratio, m , and cloud cover, f , are prognostic variables, and two prognostic equations are added to the model, following Tiedtke (1993).

$$\frac{dm}{dt} = (\dot{m})_{ST} + (\dot{m})_{CV} + (\dot{m})_{PP} + (\dot{m})_{EC}, \quad (2a)$$

$$\frac{df}{dt} = (\dot{f})_{ST} + (\dot{f})_{CV} + (\dot{f})_{PP} + (\dot{f})_{EC}, \quad (2b)$$

where $(\dot{})$ is the rate of change, and subscripts ST , CV , PP and EC stand for changes due to stratiform cloud, convective cloud, precipitation and evaporation of cloud, respectively. The cloud water mixing ratio has units of kg/kg. Advection of cloud is not considered in the model, because of a decreased importance in low resolution modeling.

Several environmental effects caused by the explicit cloud scheme are added to the equations of temperature, T , and specific humidity, q .

$$\frac{dT}{dt} = A(T) - \frac{L}{C_p} \{(\dot{q})_{ST} + (\dot{q})_{EC} + (\dot{q})_{ER}\}, \quad (2c)$$

$$\frac{dq}{dt} = A(q) + (\dot{q})_{ST} + (\dot{q})_{EC} + (\dot{q})_{ER}, \quad (2d)$$

where subscript ER stands for the change due to evaporation of rain, and $A(T)$ and $A(q)$ represent

Fig. 1. The processes considered in the explicit scheme.

terms without the explicit cloud scheme. Changes due to advection, cumulus convection and turbulence, etc. are included in the terms, $A(T)$ and $A(q)$. $(\dot{q})_{ST}$ and $(\dot{q})_{EC}$ are equal to $-(\dot{m})_{ST}$ and $-(\dot{m})_{EC}$, respectively. The processes considered in the explicit scheme are schematically illustrated in Fig. 1.

Since the FSU-GSM does not carry specific humidity as a variable in the upper three sigma levels ($\sigma = 0.06, 0.08$ and 0.14), cloud cover and cloud water are assumed to be equal to zero in those levels. σ is equal to 0.25 at the uppermost cloud level.

3.2 Formation and dissipation of stratiform cloud

We calculate the condensation or evaporation of cloud using the changes of T and q by non-convective processes, such as large-scale vertical motion and radiative cooling and heating, and so on. This scheme is somewhat similar to the Sundqvist scheme (1978) in a way, but it differs from his scheme in that the cloud cover is also predicted, while it is diagnostically calculated from relative humidity in his scheme. The parameterization of cloud cover and cloud water is deduced from the assumptions below.

3.2.a. Assumptions

The rate of changes of cloud water, $(\dot{m})_{ST}$, and cloud cover, $(\dot{f})_{ST}$, due to stratiform cloud processes are calculated using the following assumptions, that constitute a key aspect of the present scheme.

- (i) Temperature is uniform in a grid box. Therefore, saturated humidity, q_s , is also uniform.
- (ii) Specific humidity varies in a grid box. If cloud cover is not zero, q is equal to q_s in the overcast area within the grid box. The value of q is evenly distributed between a minimum value and q_s in the open area within the grid box.
- (iii) The value of cloud water is evenly distributed between 0 and a maximum value in the overcast area within the grid box.

(iv) Changes of T and q are uniform in a grid box.

(v) Cloud starts to form if the relative humidity exceeds a critical value, which is prescribed.

The assumptions about temperature in (i) and (iv) imply that the latent heat released in the cloud is somehow transported to the open area by an efficient adjustment process. Simple distributions of q in the open area (ii) and of m in the overcast area (iii) are adopted as a first attempt. The minimum value of moisture and maximum value of cloud water referred to in the assumptions (ii) and (iii) are determined so that the amount of moisture or cloud water in a grid box should be equal to the grid-averaged value, which is calculated by the model. These assumptions are similar to those in Le Treut (1990), though he assumes that the value of total water (defined as water vapour plus cloud water) is distributed evenly around the grid-averaged value.

3.2.b. Relation between temperature and moisture changes

Some relations between temperature and moisture changes with and without stratiform cloud processes are mentioned first. δT , δq and δp are the rate of change of T , q and pressure, p , respectively, caused by advection and physical processes excluding the cloud processes; they will be mentioned in more detail in Subsection 3.7. δT , δq and δp are calculated by the model and are known variables. ΔT , Δq , Δq_s , Δm and Δf are the rate of change of T , q , q_s , m and f , respectively, including the stratiform cloud processes. There are five unknowns to be solved. $(\dot{m})_{ST}$ and $(\dot{f})_{ST}$ are equal to Δm and Δf , respectively.

The temperature and humidity changes, δT , δq , are modified by the cloud water condensation/evaporation, Δm . This process is expressed by the following equations:

$$\Delta T = \delta T + \frac{L}{Cp} \Delta m, \quad (3)$$

$$\Delta q = \delta q + \Delta m, \quad (4)$$

where L and Cp are the latent heat of condensation and the specific heat of dry air at constant pressure, respectively. The Clausius-Clapeyron equation and an approximate equation of the relation between q_s and e_s , saturated water vapour pressure, are as follows:

$$\frac{1}{e} \Delta e_s = \frac{\varepsilon L}{RT^2} \Delta T, \quad (5)$$

$$q_s = \frac{\varepsilon e_s}{p} \quad (6)$$

where e is water vapour pressure, R is the gas constant, and ε is equal to 0.622 .

Eqs. (5) and (6) yield Eq. (7)

Fig. 2. A schematic of the distribution of water vapour in a grid box when stratiform cloud forms. The solid line shows the distribution of the water vapour within the grid box before the condensation is calculated. The cloud water that may exist at the previous time step is not shown in the diagram. The shaded area shows the cloud water condensed in a time step.

Table 2. Sigma levels and critical relative humidity used in the explicit cloud predicting scheme.

	Sigma level	RH_C
High	0.245	0.4
	0.346	0.4
Middle	0.447	0.5
	0.548	0.5
	0.648	0.5
Low	0.748	0.66
	0.825	0.66
	0.875	0.66
	0.925	0.98
	0.970	0.99
	0.995	0.99

$$\frac{\Delta q_s}{q_s} = \frac{\varepsilon L}{RT^2} \Delta T - \frac{\delta p}{p}. \quad (7)$$

Equation (7) means that saturated humidity change is caused by temperature change and/or pressure change.

Two other equations are necessary to solve the system. Before deriving the two other equations, a term $\delta q - \Delta q_s$, which will appear frequently, is calculated using Eqs. (3) and (7).

$$\delta q - \Delta q_s = M - \gamma \Delta m, \quad (8)$$

where

$$M = \delta q + \frac{q_s}{p} \delta p - \frac{\varepsilon L q_s}{RT^2} \delta T, \quad (9)$$

$$\gamma = \frac{\varepsilon L^2 q_s}{RC_p T^2}. \quad (10)$$

M and γ can be calculated from known variables. Note that Eqs. (3), (4), (7) and (8) are derived without any cloud assumptions.

3.2.c. Formation process

When M is greater than 0 (*i.e.* water vapour increases or temperature decreases) water vapour con-

denses and turns into cloud water if saturated, while q_s may increase by $\tau \Delta q_s$ due to temperature change caused by advection and/or condensation, where τ is the time increment. Therefore, condensation occurs where specific humidity exceeds $q_s + \tau \Delta q_s$, not q_s .

Figure 2 schematically depicts this process, and we can derive two equations:

$$\Delta m = (\delta q - \Delta q_s) \left(f + \frac{\tau}{2} \Delta f \right), \quad (11)$$

and

$$\frac{\Delta f}{\delta q - \Delta q_s} = \frac{1 - f}{q_s - q_{\min}}. \quad (12)$$

In order to express $q_{\min}$ by the known variables, the following equation is derived, which dictates that the amount of moisture in a grid box should be equal to the grid-averaged value, assuming (ii) in the Subsection 3.2.a.

$$q_s f + \frac{1}{2} (q_{\min} + q_s) (1 - f) = q. \quad (13)$$

By Eq. (13), Eq. (12) becomes Eq. (12'), eliminating $q_{\min}$.

$$\Delta f = \frac{(\delta q - \Delta q_s)(1 - f)^2}{2(q_s - q)}. \quad (12')$$

We have five equations, Eqs. (3), (4), (7), (11) and (12') with five unknowns, or three equations, Eqs. (8), (11) and (12') with three unknowns (Δm , Δf and Δq_s), so that we can solve these systems of equations.

The solution is as follows:

$$\Delta m = \frac{1}{2\gamma^2 \lambda} \left[2M\gamma\lambda + \gamma f + 1 - \sqrt{(\gamma f + 1)^2 + 4M\gamma\lambda} \right], \quad (14)$$

where

Fig. 3. A schematic of the distribution of water vapour and cloud water in a grid box when stratiform cloud dissipates. The solid line shows the distribution of the water vapour and cloud water within the grid box. The heavily shaded area shows the cloud water at the previous time step. The lightly shaded area shows the cloud water after the dissipation is calculated.

$$\lambda = \frac{(1-f)^2 \tau}{4(q_s - q)}. \quad (15)$$

Δf can be easily obtained from Eqs. (12') and (8) after Δm is known. Thus Δm and Δf can be calculated, if δT , δq and δp are given.

These equations can form cloud even if there is no cloud at first. Hence, we assume that no clouds can form when the relative humidity, RH , is less than the critical relative humidity, RH_C , which is a given parameter listed in Table 2. The values are assumed to be equal to the RH_C for the diagnostic scheme.

3.2.d. Dissipation process

We can derive these equations in a similar way to the cloud formation. Equations (3) through (10) derived in Subsection 3.2.b. are common to this case. Figure 3 schematically depicts this process.

When M is smaller than 0 (*i.e.* water vapour decreases or temperature increases) cloud water evaporates and turns into water vapour if unsaturated, while q_s may decrease by $\delta t \Delta q_s$ due to a temperature change caused by advection and/or evaporation. Therefore, evaporation occurs when the specific humidity becomes less than $q_s + \tau \Delta q_s$ (Δq_s is negative), not q_s . $2m/f$ is a maximum value of cloud water, assuming (iii) in the Subsection 3.2.a. We can derive two equations:

$$\frac{\Delta f}{\delta q - \Delta q_s} = \frac{f}{2m/f}, \quad (16)$$

and

$$\frac{2(m + \tau \Delta m)/(f + \tau \Delta f)}{f + \tau \Delta f} = \frac{2m/f}{f}, \quad (17)$$

which yield

$$\Delta m = \frac{m \Delta f}{f} \left(2 + \frac{\tau \Delta f}{f} \right). \quad (17')$$

$(\Delta f/f)^2$ is not neglected in Eq. (17'), because $\tau \Delta f/f$ is -1 when the cloud disappears. When $\tau \Delta f/f$ is -1 , Δm becomes $\Delta f m/f$ from Eq. (17'), so that the cloud water becomes zero when the cloud disappears (cloud cover becomes zero). Eqs. (16), (17') and (8) yield the solution as is shown in Eq. (18):

$$\Delta f = \frac{1}{\gamma \tau} \left[-(1 + f\gamma) + \sqrt{(1 + f\gamma)^2 + \frac{\gamma \tau f^2 M}{m}} \right]. \quad (18)$$

Δm is calculated from Δf by Eq. (17').

3.3 Convective cloud formation

The FSU-GSM uses a modified Kuo scheme (Krishnamurti *et al.*, 1983). This scheme calculates total condensation in a column and the time tendency of T and q at each level, although the scheme does not tell where the cloud water is supplied.

We made the following assumptions to calculate the cloud water source. The change of temperature and moisture by the modified Kuo scheme are not altered.

(i) The vertically integrated cloud water source is equal to the total condensation in the column, P , calculated by the modified Kuo scheme. This assumption is based on the conservation of water.

$$P = \int \rho(\dot{m})_{CV} dz. \quad (19)$$

(ii) The amount of cloud water source at each level is proportional to a vertical distribution function, D .

$$(\dot{m})_{CV} \propto D(p). \quad (20)$$

A vertical distribution function is arbitrarily given. We choose a linear function as a first attempt. We tested a function with uniform distribution in height, but it made too much cloud water at the

Fig. 4. A schematic of the distribution of water vapour and cloud water in a grid box to determine the cloud cover of cumulus cloud. The shaded area shows the cloud water.

high layers. Therefore, we tune the ratio of top to bottom, so that the amount of high cloud is not abnormal. In the current paper, we use the distribution function, D , which is equal to 1 at the cloud base and equal to 0.4 at the cloud top, and is linear between the base and cloud top. Cloud top and cloud base are determined by the modified Kuo scheme.

Cloud cover is determined in the following way: First, we calculate the “diagnostic” cloud cover, f_{CV} . We assume that the value of total water, $q+m$, is evenly distributed within the grid box, where m is the value after the cloud water is increased by $(\dot{m})_{CV}\tau$. The distribution assumption is similar to that in Le Treut (1990), in which the distribution is used to split total water into a vapour part and a liquid part, provided that $q+m$ and its maximum and minimum values are given. Each value of q and m is given in this scheme, however. This assumption is schematically depicted in Fig. 4, and is represented in the equations below.

$$\frac{2m/f}{f} = \frac{q_s - q_{\min}}{1 - f}. \quad (21)$$

Combining Eqs. (13) and (21), we get

$$f_{CV} = \left(1 + \sqrt{\frac{q_s - q}{m}}\right)^{-1}. \quad (22)$$

This equation means that if the air is wet ($q_s - q$ is small), even a small amount of cloud water produces a large cloud cover, and that if the air is dry ($q_s - q$ is large), cloud cover is small. The cloud cover is also a function of cloud water. The larger cloud water makes a larger cloud cover. Note that f_{CV} does not mean the increment of cloud cover.

We assume that cloud cover becomes f_{CV} only when f_{CV} is greater than f_{t-1} , the cloud cover at the previous time step, because we assume convection does not decrease the cloud cover. Therefore, the equation is expressed as follows:

Table 3. Parameters used in parameterization of precipitation. Two parameters separated by a slash listed as m_0 and C_0 stand for stratus cloud and cumulus cloud, respectively.

m_0	$5 \times 10^{-4}/3 \times 10^{-4}$	kg/kg
C_0	$10^{-3}/10^{-4}$	s^{-1}
C_1	300	$(\text{kg m}^{-2}\text{s}^{-1})^{-1/2}$
C_2	0.5	$K^{-1/2}$
K_{ER}	10^{-5}	$(\text{kg m}^{-2}\text{s}^{-1})^{-1/2}\text{s}^{-1}$
K_{EC}	10^{-6}	s^{-1}
T_1	233	K
T_2	273	K

$$(\dot{f})_{CV} = \begin{cases} (f_{CV} - f_{t-1})/\tau & \text{for } f_{CV} > f_{t-1} \\ 0 & \text{for } f_{CV} \leq f_{t-1} \end{cases}. \quad (23)$$

3.4 Precipitation processes

The precipitation process makes use of the Sundqvist scheme for conversion of cloud water to raindrops, and a cloud ice sedimentation is also considered. Once the cloud water turns into hydrometeors, they are regarded as reaching the ground in the same time step.

Since the model does not carry the separate variables for cloud ice and cloud water, the proportion of cloud liquid water in cloud water, R , is diagnostically prescribed by the function:

$$R = \begin{cases} 0 & \text{for } T < T_1 \\ -2 \left(\frac{T - T_1}{T_2 - T_1} \right)^3 + 3 \left(\frac{T - T_1}{T_2 - T_1} \right)^2 & \text{for } T_1 < T < T_2 \\ 1 & \text{for } T > T_2 \end{cases}, \quad (24)$$

where T_1 and T_2 are listed in Table 3. Equation (24) gives a smooth transition between frozen and liquid states. Ice cloud and liquid cloud are considered separately; cloud is assumed to be divided into liquid cloud, whose cloud liquid water content and cloud cover are equal to Rm and Rf , respectively, and ice cloud, whose cloud ice content and cloud cover are equal to $(1 - R)m$ and $(1 - R)f$, respectively. Therefore, cloud water/ice content in the overcast area, m/f , does not change.

3.4.a. Cloud to raindrops

A formula by Sundqvist (1978) is modified and adopted in this scheme. The conversion rate of cloud water to rain, P_{liq} , is expressed by Sundqvist's formula as follows:

$$P_{liq} = C_T m F, \quad (25)$$

where

$$F = 1 - \exp \{ -(m/fm_C)^2 \}. \quad (26)$$

Equations (25) and (26) mean that if cloud liquid water, m/f , is smaller than a critical value, m_C , the conversion rate is very small. If cloud liquid water, m/f , is larger than m_C , the cloud water is reduced to zero with the time constant, C_T^{-1} . Therefore, if $C_T\tau$ is greater than 1, which sometimes occurs in a GSM with a large time step, then cloud will disappear with all the cloud water turning to precipitation. Since it is not appropriate, the formula is modified to the one below:

$$P_{liq} = C_T R(m - fm_C F) F. \quad (27)$$

This modified Eq. (27) means that cloud water, m/f , is reduced to the critical value, m_C , at the time constant of C_T^{-1} , instead of being reduced to zero in the Sundqvist formula (25), when m/f is greater than m_C .

C_T and m_C are expressed as follows:

$$C_T = C_0 f_{CO} f_{BF}, \quad (28)$$

$$m_C = m_0 / (f_{CO} f_{BF}), \quad (29)$$

$$f_{CO} = 1 + C_1 \sqrt{\tilde{P}}, \quad (30)$$

$$f_{BF} = \begin{cases} 1 + C_2 \sqrt{268 - T} & \text{for } T < 268 \\ 1 & \text{for } T > 268 \end{cases}, \quad (31)$$

where the rate of precipitation, $\tilde{P}$, will be defined later in this section, and m_0 , C_0 , C_1 , C_2 are constants listed in Table 3.

Different values are used for cumulus cloud and stratiform cloud as in Sundqvist *et al.* (1989). Grid points where the condensation due to the modified Kuo scheme occurred are regarded as cumulus cloud, unless the level considered is cloud top and the sigma level is less than 0.3. We assume that the conversion of cloud water to rain does not change the cloud cover.

3.4.b. Cloud ice sedimentation

The fall speed of cloud ice is not negligible compared to that of cloud liquid water. We take this effect into account. The rate of change of cloud ice by flux divergence, S , is expressed as follows:

$$S = g \frac{dF_{ICE}}{dp}, \quad (32)$$

$$F_{ICE} = (1 - R)f(\rho m_i v),$$

where m_i is cloud ice mixing ratio in cloud ($= m/f$), ρ is the density of air and v is the fall speed of cloud ice. Here v is deduced from observation by Heymsfield (1977):

$$v = 3.326(\rho m_i)^{0.17}, \quad (33)$$

where v and ρ are in units of m/s and kg/m³, respectively.

If S is positive, it is counted as precipitation, instead of considered toward the increase of cloud ice content. The reason is as follows: if the divergence

of ice flux is positive, cloud ice should increase, but cloud liquid water should not, provided that the temperature is below the freezing point. In the model, however, since the ratio of liquid and ice is given by a function of temperature, cloud ice as well as cloud liquid would increase. Because the increase of cloud liquid is not reasonable, the increase of m is assumed to be converted to precipitation. Therefore, the conversion rate of cloud ice to precipitation due to sedimentation, P_{ice} , is expressed as follows:

$$P_{ice} = S \text{ for } S > 0, \\ 0 \text{ for } S < 0. \quad (34)$$

We assume that while cloud ice falls, its cloud cover remains unchanged and the density of cloud water in overcast area decreases, except for the case where the cloud ice content becomes zero. Then, a portion of cloud cover by ice cloud, $(1 - R)f$, is assumed to be removed.

$$(\dot{f})_{PP} = \begin{cases} (1 - R)f/\tau & \text{for } P_{ice}\tau > (1 - R)m \\ 0 & \text{for } P_{ice}\tau \leq (1 - R)m \end{cases}. \quad (35)$$

3.4.c. Evaporation of raindrops

Sundqvist's formula is adopted for the evaporation of raindrops.

$$(\dot{q})_{ER} = K_{ER}(1 - f)(1 - RH)\sqrt{\tilde{P}}, \quad (36)$$

where K_{ER} is a constant listed in Table 3. Evaporation of raindrops is not considered between the cumulus cloud base and top, because it should be included in the modified Kuo scheme.

3.4.d. Change rate of cloud due to precipitation and flux of precipitation

The change rate of cloud water due to precipitation $(\dot{m})_{PP}$, and the flux of precipitation, $\tilde{P}$, are calculated as follows:

$$(\dot{m})_{PP} = S - P_{liq} - P_{ice}, \quad (37)$$

$$\tilde{P} = \frac{1}{g} \int_0^P \{P_{liq} + P_{ice} - (\dot{q})_{ER}\} dp. \quad (38)$$

Total precipitation on the ground is the sum of $\tilde{P}$ and F_{ICE} .

We assume that no cloud is left at the lowest level ($\sigma = 0.995$), because the physical processes of the GSM such as vertical turbulence transfer are not so accurate as to represent fog in the surface layer. Therefore, $(\dot{m})_{PP}$ and $(\dot{f})_{PP}$ are expressed as follows at the level.

$$(\dot{m})_{PP} = -m/\tau,$$

$$(\dot{f})_{PP} = -f/\tau.$$

Fig. 5. The time change of global mean total cloud cover (%) in six-hourly data by the P-STD run (—), the P-CUM run (---), the P-ANV run (····), the D-STD run (-·-·-) and the D-RHC run (- - -).

3.5 Evaporation of cloud

Evaporation of cloud due to turbulent mixing of cloud air and unsaturated environmental air is considered in addition to the dissipation of stratiform cloud. We follow Tiedtke (1991).

$$(\dot{m})_{EC} = -K_{EC}f(q_s - q), \quad (39)$$

$$(\dot{f})_{EC} = (\dot{m})_{EC}/m, \quad (40)$$

where K_{EC} is a constant listed in Table 3. These equations imply that the density of cloud water in overcast area remains unchanged while cloud cover is reduced by this process.

3.6 Initial condition

The initial value of the cloud variables is given in a simple way, which is similar to that adopted by Pudykiewicz *et al.* (1992). At first, the cloud cover is diagnosed with Eq. (1), though RH_m is the relative humidity of each layer in the column. Then we assigned the cloud water content, CWC , in units of kg m^{-3} by Eq. (41).

$$CWC = 10^{((T-273)/20-4)}, \quad (41)$$

The maximum value of CWC is limited to $5 \times 10^{-5} \text{ kg/kg}$.

3.7 Numerical procedure

The numerical procedure should be taken care of because most of the condensation precipitates out and only a small portion remains as cloud water during one time step of the global model. Time step of physical processes is 40 minutes in the present model.

The following procedure is adopted in this scheme. After the increments of m and f are calculated in

Fig. 6. Latitudinal distribution of zonal mean total cloud covers of the P-STD run at Days 1 (—), 3 (---), 5 (---), and 7 (-·-·-).

the first process, they are added to m and f , respectively, to obtain a set of interim values, m^* and f^* . The next process is calculated using the interim values, m^* and f^* , then another set of interim values, m^{**} and f^{**} , are obtained. The same procedure is continued in each process.

The order to calculate each process makes a large difference on the results. The processes to produce cloud water are calculated before those to reduce cloud water, basically. The order of each process is as follows:

- (1) Convective cloud formation.
- (2) Stratiform cloud formation and dissipation.
- (3) Removal of supersaturation.
- (4) Precipitation processes and evaporation of raindrops.
- (5) Evaporation of cloud by turbulent mixing.

The terms δT and δq are calculated as follows: The term δT is the summation of the rate of change by vertical advection, turbulent transfer, convective adjustment, and radiation. The term δq is the same except that it does not include the radiation term. The rate of change by convective adjustment is mentioned later in Subsection 3.9. After the modified Kuo scheme is invoked, vertical advection terms are subtracted both from δT and δq , since vertical motion is assumed not to form stratiform cloud any more where the convective cloud is formed.

3.8 Radiation scheme

The predicted values of cloud water content and cloud cover are provided for the radiation scheme, in which optical depth and emissivity are calculated using cloud water content.

Emissivity, ε_{IR} , used in long wave radiation is calculated by the following equation.

Fig. 7. Latitudinal distribution of zonal mean total cloud covers averaged from Day 1 to Day 7. (a) the P-STD run (—), the P-CUM run (---) and the P-ANV run (-·-·-). (b) the P-STD run (—), the D-STD run (---) and the D-RHC run (-·-·-).

$$\varepsilon_{IR} = 1 - \exp(-kW), \quad (42)$$

where W is the cloud water path (g/m^2). $k = 0.14$ (Stephens, 1978) for cloud liquid and $k = 0.05$ (Starr and Cox, 1985) for cloud ice.

The optical depth, T_{SW} , used in short wave radiation is given as follows:

$$T_{SW} = \exp(0.6063 + 3.9363 \log(\log_{10}(W))) \quad (43a)$$

for cloud liquid (Stephens, 1978), and

$$T_{SW} = (-0.75)^{-1} 0.05W \quad (43b)$$

for cloud ice.

Equation (43b) is obtained in the following manner. Platt and Harshvardhan (1988) derived an expression

$$\varepsilon_{IR} = 1 - \exp(-0.75T_{SW}). \quad (44)$$

On the other hand, ε_{IR} is obtained by Eq. (42) in this scheme. We can get Eq. (43b) by equating two emissivities by Eqs. (44) and (42).

Optical depth and emissivity are calculated separately for liquid and ice, then they are weight averaged by the amount of liquid and ice. The proportion of liquid water in cloud water is expressed in Eq. (24).

3.9 Modification of dry convective adjustment

The dry convective adjustment scheme adopted in the FSU-GSM is modified. It is performed as follows in the current model: If the atmosphere is unstable, the lapse rate of the temperature is made to be dry adiabatic in the unstable layers, which implies cooling in the lower layers and warming in the upper layers. Then, condensation is calculated so that the relative humidity of the layers where temperature decreases due to the adjustment should not change. Therefore, water vapour is removed in the lower portion of the unstable layers. Removal of the water vapour, however, is not regarded as a cloud water condensation, because it would be unrealistic that the cloud is formed in the lower portion of the adiabatic layers.

Hence, the adjustment scheme is modified to the following formation. Thermodynamic and water content variables which are conserved during the changes of state of cloud water are defined as follows:

the liquid water temperature,

$$T_l = T - (L/C_p)m, \quad (45a)$$

and the total water content,

$$q_t = q + m. \quad (45b)$$

These values are defined by Betts (1973) and are used in the cloud water prediction scheme by Smith (1990).

In the modified adjustment scheme, T_l and q_t are calculated at first. Then the stability is checked; the lapse rate of T_l , Γ , is made equal to the dry adiabatic lapse rate Γ_d , if unstable. The change of the total water is calculated in the layers where the lapse rate is modified to Γ_d , so that q_t is constant throughout the layers, conserving the total amount in the column. Thus, we get the changes of liquid water temperature, T_l , and total water, q_t , though we do not know the individual changes of temperature, moisture and cloud water. We assume that the change of cloud water is equal to zero at this point, and get the change of temperature and moisture. They are provided for the stratiform cloud scheme and condensation or evaporation would then be calculated. In this scheme, the cloud can be formed in the upper portion of the layers where adjustment occurred, which is reasonable.

4. Numerical results

4.1 Forecast experiments

Five 7-day forecasts were performed to study the influence of the explicit cloud scheme, the convective

Fig. 8. Geographical distribution of total cloud covers by the P-STD run(a) and the D-STD run(b). The contour interval is 25 %.

cloud, and the tuning of the critical relative humidity in the diagnostic cloud scheme. The same initial conditions of 1200UTC 1 July 1987 were used for the experiments. The P-STD run uses the explicit cloud-predicting scheme described in Section 3, while the D-STD run uses the diagnostic cloud scheme mentioned in Section 2. Two other runs with the explicit cloud-predicting scheme were performed. The P-CUM run has no convective cloud. All the condensation calculated by the modified Kuo scheme is precipitated out in this run. Therefore, no cloud is left at the grid point where the convective clouds are predicted. The P-ANV run is similar to the P-CUM run, but the cloud water and cover at the top of the convective cloud are calculated as the P-STD run if the sigma-level of the cloud top is higher than 0.2. Only "anvil cloud" is left in this run concerning the convective clouds. Stratiform clouds in the P-CUM and the P-ANV runs are calculated in

the same way as the P-STD run. The D-RHC run is performed to increase the high clouds in the tropics with the diagnostic cloud scheme. RH_C in Eq. (1) is reduced to -0.25 for the high clouds in the tropics. Then, the cloud cover is 4 % even if the relative humidity is 0 %. This assumption may seem absurd, but it is performed only for experimentation.

4.2 Cloud cover

4.2.a. Time change of the total cloud cover

The time rate of change for the global mean total cloud cover in the six-hourly data is shown in Fig. 5. Total cloud cover in a grid column is obtained by the assumptions of maximum overlap within contiguous cloud levels and random overlap between the different contiguous cloud levels.

The cloud cover predicted by the P-STD run is more than 40 % during the majority of the forecast period, closer to the conventional estimate (about

Fig. 9. Geographical distribution of high cloud covers between 30°S and 30°N by the P-STD run(a), the P-ANV run(b), the D-STD run(c) and the D-RHC run(d). The contour interval is 20 %.

50 %) than those by other runs. On the other hand, the cloud cover by the D-STD run is less than 30 %. The D-RHC run predicts more cloud cover than the D-STD run by about 5 %, but the value is still less than the conventional estimate. Cloud cover by convective cloud is not negligible in the model. Cloud covers predicted by the P-ANV run and the P-CUM run are less than that by the P-STD run by about 10 % and 15 %, respectively.

Cloud cover by the model decreases gradually throughout the forecast period, as is pointed out by Krishnamurti *et al.* (1988). This tendency is not corrected in the explicit cloud scheme either. The zonal mean cloud cover by the P-STD run at Days 1, 3, 5 and 7 is shown in Fig. 6. The decreasing tendency between 30°S and 30°N from Day-1 to Day-5 can be seen. Especially a decrease of the maximum at 10°N is evident. Such a tendency is not as clear in other latitudes. These features are common to

the other four runs (not shown). Cloud cover increases in the first 24 hours of the forecast in the explicit scheme, however. The initial description of the cloud needs to be improved. The values averaged from Day 1 to Day 7 are used hereafter in order not to include the transient stage starting from the initial condition.

4.2.b. Time-averaged total cloud cover

The zonal mean total cloud coverage averaged from Day 1 to Day 7 is shown in Fig. 7. The basic meridional structure of the cloud cover is well captured by the P-STD run (Fig. 7a). The maxima are located at 60°S, 10°N, and 50°N, and their values are about 75 %, 60 % and 55 %, respectively. The minima between them are about 30 %. The locations of maxima agree with an analysis done by Stowe *et al.* (1989), and the values are reasonable. Note that Stowe *et al.* (1989) showed a one-month

Fig. 10. Same as Fig. 7a, but for vertically integrated cloud water. The vertically integrated cloud liquid water over the ocean is also shown (---).

mean of July 1979, which is different from the period of these experiments. The cloudiness over the Arctic is less than that of observations.

Cloud cover by convective cloud is not negligible except in the polar region, and the anvil cloud is important mainly in the tropics. Fig. 7a shows that the maximum in the tropics by the P-CUM run is notably low, while the P-ANV run has a distinct maximum in the tropics. The maximum values in the tropics by the P-STD, the P-ANV and the P-CUM runs are, respectively, 60 %, 43 % and 28 %. Therefore, about half of the cloud cover in the ITCZ (inter tropical convergence zone) is produced by convective cloud, and the "anvil cloud" accounts for about half of the cloud from convective cloud.

The D-STD and D-RHC runs produced less cloud amount than the P-STD run at all latitudes except for south of 70°S and north of 80°N (Fig. 7b). The maxima in the mid-latitudes by the D-STD and the D-RHC runs are located at different places from those by the P-STD run. The result of the D-RHC run shows that tuning the parameter RH_C can increase the cloud cover.

The geographical distribution of total cloud cover by the P-STD run (Fig. 8a) resembles an analysis by Stowe *et al.* (1989) more than does the D-STD run (Fig. 8b). Fig. 8a shows that the ITCZ is represented clearly by the P-STD run. Storm tracks in the north Pacific and the north Atlantic are also represented. The minima over Australia, South Africa, North Africa to Middle East, South America and over the subtropical oceans to the north and south of the ITCZ are also reproduced. In the southern hemisphere, the P-STD run generates much cloud over the ocean (between 40°S and 60°S) and little cloud over the Antarctica. However, the P-STD run cannot represent the stratocumulus cloud off the west coast of California, Chile and South Africa.

Figure 8b shows that the D-STD run qualita-

tively represents the characteristic distribution of the clouds such as the ITCZ and the storm track in the North Pacific, but the cloud amount is much smaller than for the P-STD run. The D-STD run has a maximum near the coast of Antarctica (around 60°S and 70°S) that is different from the results of the P-STD run. The zonal mean (Fig. 6) reflects this feature in the southern hemisphere.

4.2.c. Time-averaged high cloud cover

The distribution of the high cloud cover shows the importance of the convective cloud more clearly. Figure 9 shows the geographical distributions of high clouds, which are also averaged from Day 1 to Day 7. The cloud cover is calculated assuming maximum overlap of the clouds on the sigma-levels of 0.245 and 0.346. The result of the P-CUM run, which produces a very small amount of high cloud, is not shown.

The majority of the cloud cover from the high cloud is supplied by the convective cloud. The results of the P-STD (Fig. 9a) and the P-ANV (Fig. 9b) runs are similar, though the P-ANV run produces less overall cloud amount. They illustrate the ITCZ, cloud maxima to the west of Central America and around India. The maximum values of the zonal mean of high cloud in the tropics by the P-STD and the P-ANV runs are 30 % and 24 %, respectively, which are similar in magnitude as Stowe *et al.* (1989) shows. On the other hand, the D-STD (Fig. 9c) run shows much less cloud amount in the tropics. The cloud cover exceeds 20 % only over the Indian ocean to eastern Africa and a small portion of America. The maximum value of the zonal mean in the tropics by the D-STD run is 8 %.

Zonal mean cloud amounts by the D-RHC run are increased by tuning the parameter RH_C , although the geographical distribution is different from the P-STD run. The D-RHC run (Fig. 9d) expresses more cloud than the D-STD run, and the maximum value of the zonal mean is about 27 % in the tropics, which is as much as that by the P-STD run. The geographical distribution, however, is different from the P-STD run, *e.g.*, around Central America, the Western Pacific, and Southeast Asia.

4.3 Vertically integrated cloud water content

The cumulus clouds account for most of the cloud water in the tropics, and almost half in the mid-latitudes. Anvil cloud does not contribute much to the cloud water, though it is important for the cloud cover. The zonal mean of the vertically integrated cloud water of the P-STD, the P-CUM and the P-ANV runs is shown in Fig. 10. No cloud water is expressed by the diagnostic scheme. The P-CUM and the P-ANV runs have less cloud water than the P-STD run. Especially in the tropics, the maximum is obscure in the P-ANV run, and is not expressed by the P-CUM run.

Fig. 11. Geographical distribution of vertically integrated cloud water content of the P-STD run. The contour interval is 0.08 kg/m^2 .

The cloud liquid water of the P-STD run is compared to the satellite-observed data. Greenwald *et al.* (1993) have shown the vertically integrated and zonally averaged cloud liquid water over the ocean derived from SSM/I data, and averaged in August 1987. The zonal mean of the vertically integrated cloud liquid water over the ocean by the P-STD run is also shown in Fig. 10 for comparison. Note that the observed period is different from the prediction period. Comparing the results of the model and their analysis, the general features such as maxima in the tropics and minima in the subtropics are well captured by the model. However, we find that the maximum in the high latitudes in the northern hemisphere is shifted north and the value is overestimated, and that cloud liquid water between the equator and 20°S is underestimated by the model.

The geographic distribution of cloud water content by the P-STD run is shown in Fig. 11. High values can be found in the ITCZ and between 30°S and 60°S in the regions of mid-latitude perturbations as well as in storm tracks in the North Atlantic and the North Pacific. On the other hand, the P-CUM and the P-ANV runs (not shown) have little cloud water in the tropics, and the cloud water amount in the mid-latitudes was much smaller than the P-STD run, as was witnessed from the zonal mean.

4.4 OLR

The model-calculated OLR is compared with observed data. The model-produced OLR is averaged from Day 1 to Day 7. The observed data is averaged from 12UTC 2 July to 12UTC 8 July, and has the horizontal resolution of 2.5 degrees latitude by longitude. Validation of the cloud scheme by the radiation measurements is an approximate method,

because of the difficulty of prescribing cloud optical properties and the problem of cloud layer overlap. Considering the uncertainty in deriving cloud water or cloud cover from satellite-observed data, however, validation by OLR is as proper a way as that by cloud cover or cloud water.

Figure 12b shows that the latitudinal variation by the P-STD run is improved from the D-STD run, although the predicted value is about 25 W/m^2 larger than the observed value, on the average. The P-STD run represents the minimum in the tropics, *i.e.*, the ITCZ, better than the D-STD run. It also represents the change of the inclination around 70°S which the two runs with the diagnostic scheme cannot represent.

Although the zonal mean of the P-STD and the D-RHC runs are similar to each other in the tropics (Fig. 12b), there are some important differences in the geographical distribution. Figure 13 shows that the P-STD run can capture some observed features over the ITCZ, which the D-STD or D-RHC runs do not. First, the ITCZ over the Atlantic Ocean, Central America and the Eastern Pacific Ocean are represented by the P-STD run better than by the two runs with the diagnostic scheme. Especially, off the east coast of Central America, the D-RHC run has a minimum at the equator, while the P-STD run and observations show the minimum around 10°N . Secondly, over India and Southeast Asia, observations show the minima over land and the Bay of Bengal. The D-STD run has a minimum over the equator, and the minimum by the D-RHC run is extended toward India and the Bay of Bengal, while the minimum from the P-STD run is shifted inland further toward the north. Maxima at the equator between

Fig. 12. Same as Fig. 7, but for zonal mean OLR. The observed value is also shown (----).

60°E and 90°E and the relatively high value over the Arabian Sea do not exist in any of the runs, however. Thirdly, over the Western Pacific, low OLR is extended to the west of 180°E between 10°N and 10°S. Three runs contain the low OLR between the equator and 10°N. The P-STD run barely shows the low OLR between the equator and 10°S to the east of New Guinea, although D-STD or D-RHC runs do not contain it at all.

The cloud with convective source plays an important role in relation to the OLR in the tropics. The cloud originating from the top of the convective cloud is essential to the OLR, even though the cloud water content is small, as was shown in Subsection 3.3. Figure 12a shows that the P-CUM run represents the minimum in the tropics very poorly. The P-ANV run represents the ITCZ as well as the P-STD run does (Fig. 12a), and produces a similar geographic distribution to the P-STD run in the tropics (not shown).

The improvement of the OLR implies that the explicit scheme expresses the cloud cover and optical properties of the high clouds in the tropics more realistically. Since these clouds originate from the

convective source, considering this kind of cloud is necessary to correctly represent the OLR.

5. Concluding remarks

A new explicit cloud prediction scheme is presented. The main feature of the scheme is that a closure of the scheme consists of assumptions of sub-grid scale distributions of cloud water and water vapour. Other features of the scheme are summarized as follows: Both cloud water and cloud cover are prognostic variables in the scheme. Source terms by cumulus cloud as well as stratiform cloud are considered. The predicted cloud water content and cloud cover are provided to the radiation scheme. Cloud liquid water and cloud ice are distinguished by a prescribed function of temperature, when precipitation rate or optical properties of the cloud are calculated. Cloud variables are not advected in the current low resolution version. The scheme produces a reasonable amount of cloud cover and cloud water.

The role of convective cloud in producing cloud cover and cloud water is shown by the several experiments with the explicit cloud scheme. We find that convective cloud produced by the model is not negligible in the total cloud cover, except for the polar regions. In the tropics, cloud provided by convection accounts for roughly half of the total cloud cover and most of the high cloud cover. Convective cloud is also an important source of cloud water. The convective clouds provide half of the cloud water in the mid-latitudes, and are an essential source of the cloud water in the tropics.

The explicit scheme improves the geographic distribution of OLR markedly over ITCZ, *e.g.*, around Central America, over the Western Pacific and Southeastern Asia. Since OLR is almost entirely controlled by the high cloud, improvement of OLR means that the high cloud is properly represented by the model. Moreover, since the high cloud originates mainly from convective cloud, we can say that the explicit cloud scheme calculates the convective cloud appropriately.

The geographical distribution of OLR with the diagnostic scheme is not much improved by tuning a parameter. The cloud cover by the diagnostic scheme is less than that by the explicit scheme, especially high cloud in the tropics, with the FSU-GSM. The amount of the cloud by the diagnostic scheme, however, can be increased by tuning the parameter RHC in Eq. (1), but the geographical distribution of high cloud as well as OLR is not much improved.

Further improvements of the scheme are necessary. First, interaction between cloud and turbulence in the boundary layer should be considered. Turbulent mixing of temperature, moisture and cloud water with an appropriate definition of stability has been already proposed by Smith (1990). This kind of process seems to be necessary to repre-

Fig. 13. Geographical distribution of OLR between 30°S and 30°N by the P-STD run(a), the D-STD run(b), the D-RHC run(c), and the observation(d). The contour interval is 20 W/m². Boundaries of shading are 220, 260 and 300 W/m² for (a), (b) and (c), and 200, 240 and 280 W/m² for (d). The blank area in (d) is less than 200 W/m².

sent the stratocumulus cloud off the coasts of Peru and California. A finer vertical resolution may be necessary. Secondly, the source term for convective cloud should be improved. The vertical distribution function employed in the current paper is a crude one. A function with a physical and/or observational basis is necessary. A different way to represent convective cloud is employed by Tiedtke (1993) and Ose (1993). Their scheme makes use of the detrainment rate calculated by a convection parameterization scheme representing mass flux, and seems to be promising. Thirdly, it is more consistent to carry the cloud liquid water and the cloud ice on separate variables as Lee *et al.* (1992) and Ose (1993) have shown. The present scheme carries one variable for the sum of liquid and ice, which is

divided by the prescribed function of temperature. Fourthly, the cloud advection should be included because it will be important when the resolution of the model becomes higher. Lastly, proper initial values of cloud variables should be supplied from observational data.

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フロリダ州立大学全球スペクトルモデルに組み込んだ雲予測スキームとその影響

萬納寺信崇¹

(フロリダ州立大学)

フロリダ州立大学全球スペクトルモデル (Florida State University-Global Spectral Model; FSU-GSM) に雲を予報するスキームを組み込み、その影響を調べた。雲水と雲量の二つを新しい予報変数として付け加える。積雲対流による雲と、大規模場の収束による雲が考えられた。大規模場の発散により、雲は消える。予想された雲量と雲水量が放射のスキームに使われる。雲の移流はいまのところ考えていない。雲水は、あらかじめ与えられた温度の関数で水(液体)と固体(氷)に分けられる。

モデルはもっともらしい雲量と雲水量を再現した。両極地方を除き、積雲から発生する雲が雲量と雲水量にとって重要である。熱帯では、積雲を起源とする雲が全雲量の半分を占め、上層雲のほとんどを占める。積雲を起源とする雲は、中緯度の雲水量の半分を供給し、熱帯では雲水量にとって不可欠である。

熱帯の外向き長波放射(OLR)が改善された。これはこのスキームが対流性の雲も考慮していることによる。対流性の雲が熱帯の上層雲には不可欠であり、これがOLRに大きな影響を及ぼす。

¹現在所属：気象庁数値予報課