NOTES AND CORRESPONDENCE

Comparison of Apportionment Schemes of Cloud Amount to Levels of a Numerical Model

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1. Introduction

In numerical prediction models, especially general circulation models (GCMs), cloud amount is one of the most important quantities that determines the radiative fluxes. There are currently two approaches for the determination of cloud amount in numerical models. One is that cloud amount is determined in a straightforward manner from cloud water content, which is one of the explicit model prognostic variables. The other is that cloud amount is diagnostically determined from some other prognostic variables in the model. Although some reports referring to cloud prediction schemes have been published (Sundqvist, 1981; Roeckner and Schlese, 1984; *etc.*), most current GCMs use the diagnostic cloud parameterization scheme in their radiation calculations. This is mainly due to the fact that cloud water content is not a prognostic variable in many GCMs. In the JMA's operational global spectral model, a statistical relation between relative humidity and cloud amount (Saito and Baba, 1988) has been used since March 1988.

Generally, statistical relationships express the connection between the two-dimensional cloud cover rate and the atmospheric state in a certain layer. Consequently, when a statistical relationship is used for the determination of cloud amount in a numerical model, the cloud amount at each level should be assigned so that it satisfies the relationship between the two. If multiple levels are included within the layer, some modification to the statistical relationship is sometimes required to adjust the false change of the total cloud cover due to the overlap of clouds. In this note, the cloud-cover parameterization schemes of the JMA's operational global models are presented, and a comparative study of some schemes for the apportionment of cloud amount to levels in a numerical model is performed with the

assumption of a random overlap of clouds.

2. Cloud cover parameterization schemes of the JMA's global models

As in several other GCMs, diagnostic cloud-cover parameterization schemes have been used in JMA's operational GCMs. Up to February 1988, the relationship developed by Smagorinsky (1960) had been used in 12-layer northern hemispheric model (12L-NHM) of the JMA. The relationship is an empirical relation formed by the analyses of synoptic data and represents the cloud amount through some linear functions of relative humidity. Since March 1988, the relationship found by Saito and Baba (1988) has been used in the new JMA 16-layer global spectral model (16L-GSM). This statistical relationship between relative humidity and cloud amount is based on satellite observations. It classifies the cloud into four layers and expresses the cloud amount by the following quadratic function of relative humidity,

$$C(r) = B \max^2(0, r - R_c) \quad (1)$$

where, C is the cloud amount, r is the relative humidity, B is a coefficient which determines the inclination of the function and R_c is the critical relative humidity above which the cloud amount increases. Classification of clouds and the values of B and R_c determined by Saito and Baba (1988) are shown in Table 1. An interesting comparison between satellite-derived and model-generated cloud was studied by Kimoto (1988), using this relation.

Figure 1 shows the vertical cloud representation and the distribution of the levels of the 16L-GSM. The classified cloud layers include multiple levels, except for the Middle-1 layer. In the ECMWF's model (Slingo, 1987) and the U.K.'s model (Dickinson, 1985), clouds are classified into two types. One is convective type clouds, which are determined from the rate of precipitation and/or mass flux in the

Table 1. The classification of cloud layers and the values of B and Rc determined by Saito and Baba (1988).

Classification of cloud	Height of layer	B	Rc
High cloud	150-400 hPa	1.05	0.15
Middle-1 cloud	400-500 hPa	0.70	0.30
Middle-2 cloud	500-700 hPa	1.00	0.35
Low cloud	700-900 hPa	1.60	0.45

Fig. 1. The vertical cloud representation and the distribution of the levels of the 16L-GSM. The value of the vertical coordinate σ (=pressure/ surface pressure) is shown at the left of each level.

model’s convection scheme. The other is stratiform clouds diagnosed from the relative humidity and/or vertical velocity. The convective type clouds can be found at all levels and maximum overlap is assumed, while stratiform clouds are classified into three layers according to their height, and for simplicity they are constrained so that they cannot exceed one level for each layer. On the other hand, in the JMA’s 16L-GSM, clouds are allowed to occur at any level except those in the surface boundary layer and above tropopause. Cloud amount is determined according to the value of relative humidity at each level from $\sigma=0.890$ to $\sigma=0.155$ shown in Fig. 1. The amounts are apportioned to each level as in Case C mentioned in Section 4. The details of the radiation calculation schemes employed in the JMA’s 16L-GSM are described in Sugi *et al.* (1989).

3. Apportionment of cloud amount to levels of a numerical model

In this section, the necessity for modification of the diagnosed cloud amount and the assumptions employed in this study are described. To generalize the statistical relationship, it is supposed that a diagnostic relation for cloud amount C in a certain layer is expressed as follows;

$C = C(\Psi)$ (2)

where, Ψ denotes the physical state of a layer and is expressed by several large-scale variables. As mentioned in Section 2, the JMA’s operational GCMs have used relative humidity r for Ψ . In other GCMs, some other large-scale variables, such as the stability index and/or vertical velocity, are at times used in addition to r .

Generally, statistical relationships express the relationship between two-dimensional cloud cover observed from the ground or satellite and the atmospheric state in a certain layer. When a statistical relationship is used for the diagnosis of cloud amount in a numerical model, the cloud amount at each level should be determined so that it satisfies the relationship between the two. If multiple levels are included in a given layer, with the cloud amount being defined at each level, the total two-dimensional cloud cover in that layer should be calculated by subtracting the overlap of cloud from the sum of the cloud amount at each level in that layer. If a maximum overlap of clouds is not assumed in a numerical model, when the cloud amount at each level is estimated by Eq.(2) using the predicted state at that level, the total cloud cover in a given layer becomes larger as the number of levels increases. In this case, some modification of the diagnostic relation is required to avoid this over-estimation. To compare several adjustment schemes for the above modification, the following assumptions are introduced in this study.

1) The cloud at each level is distributed with random overlap. Therefore, the total cloud cover C_y in a given layer is calculated as follows;

$C_y = 1 - \prod_{i=1}^N (1 - C_i)$ (3)

where N is the number of levels included in the layer, and C_i is the cloud amount at each level.

2) The diagnostic relationship expresses the relation between the averaged state $\bar{\Psi}$ and the total cloud cover C_y . That is, $C_y = C(\bar{\Psi})$ is assumed. $\bar{\Psi}$ is obtained by averaging the states of the levels included in the relevant layer.

3) The evaluation is performed by comparing C_y in Eq.(3) and the averaged diagnostic cloud amount C_{ym} with the assumption of $C_{ym} \sim C(\bar{\Psi})$. C_{ym} is defined by the following equation.

$$C_{ym} = \frac{1}{N} \sum_{i=1}^N C(\Psi_i) \quad (4)$$

Although the first assumption is currently used for the radiation calculation of several GCMs, it is not always suitable when several levels are included within a thin layer. The suitable rate of overlap should be decided by several other studies in order to correlate the cloud amount at levels of various heights. The suitability of the second assumption is influenced by the method of derivation of the diagnostic relation. In the case of the diagnostic relationship used in the JMA's 16L-GSM (Saito and Baba, 1988), it expresses the relationship between the state at a certain level and the two-dimensional cloud cover in a certain layer. The third assumption is not exactly realized when the diagnostic relationship is nonlinear. Strictly speaking, the two-dimensional cloud cover C_y should be compared to the cloud amount through the diagnostic relationship for the average state. The purpose of this study materializes when C_{ym} is replaced by $C(\bar{\Psi})$ in this case.

4. Results and discussion

The comparison of schemes for the apportionment of cloud amount to levels of a numerical model is made for the following four cases.

1) Case A; No adjustment.

In the case of no adjustment by the diagnostic relationship, the cloud amount at each level C_i is given in a straightforward manner by Eq.(2) as follows:

$$C_i = C(\Psi_i) \quad (5)$$

Figure 2a shows the ratio of C_y calculated by Eq.(3) to C_{ym} found by Eq.(4) for the case of $N=2$. The horizontal and vertical axes express the values of $C(\Psi_1)$ and $C(\Psi_2)$, respectively. The value of C_y is always larger than C_{ym} and the ratio to $C_{ym}(C_y/C_{ym})$ reaches values of 200% when $C(\Psi_1)=0$ or $C(\Psi_2)=0$. Fig. 3a shows the difference between C_y and $C_{ym}(|C_y - C_{ym}|)$. The maximum value of $|C_y - C_{ym}|$ is 0.5 when $C(\Psi_1)=1$ and $C(\Psi_2)=0$ or when $C(\Psi_1)=0$ and $C(\Psi_2)=1$. This difference becomes exceedingly large when N is large.

The maximum value of $|C_y - C_{ym}| = 0.67$ when $N=3$, and reaches 0.75 for $N=4$.

2) Case B; Divide by the number of levels.

Up to February 1988, the empirical relationship by Smagorinsky (1960) had been used in the JMA's 12L-NHM for the parameterization of cloud amount. In the 12L-NHM, cloud amounts determined at each level were divided by the number of the levels for the adjustment. Through this adjustment C_i is calculated as follows:

$$C_i = \frac{1}{N} C(\Psi_i) \quad (6)$$

Fig. 2b shows the value of C_y/C_{ym} for the case of $N=2$. Since this adjustment restricts the maximum value of C_i to $1/N$, C_y tends to be underestimated in contrast to Case A. $|C_y - C_{ym}|$ attains its maximum value of 0.25 when $C(\Psi_1)=1$ and $C(\Psi_2)=1$, as shown in Fig. 3b. This difference increases as N increases. The maximum of $|C_y - C_{ym}| = 0.30$ for $N=3$, and 0.32 for $N=4$.

3) Case C; Weighted parameter according to the cloud amount.

The weighted parameter w is used in the JMA's 16L-GSM for adjustment. The value of w for a given layer is defined as the ratio of C_{ym} to the temporary cloud cover C_{yt} . The value of C_{yt} is defined as the total cloud cover calculated by Eq.(3) and Eq.(5). That is,

$$w = \frac{C_{ym}}{C_{yt}} = \frac{\frac{1}{N} \sum_{i=1}^N C(\Psi_i)}{1 - \prod_{i=1}^N (1 - C(\Psi_i))} \quad (7)$$

therefore, the cloud amount at each level is given by multiplying $C(\Psi_i)$ by w , such as;

$$C_i = w C(\Psi_i) \quad (8)$$

Fig. 2c shows the value of w calculated by Eq.(7) for the case of $N=2$. The value of w is about $1/N$ ($=0.5$) when C_{ym} is near 0, while it approaches 1 when C_{ym} is close to 1 and adjusts C_y to a value which is close to C_{ym} . Fig. 2c shows the value of C_y/C_{ym} . The value of C_y is somewhat larger than that of C_{ym} , while the ratio is close to 1 compared to Case B. The difference $|C_y - C_{ym}|$ also becomes small with the maximum value being about 0.09, as shown in Fig. 3c.

The accuracy of this adjustment scheme becomes somewhat inferior when N increases. The maximum of $|C_y - C_{ym}|$ reaches a value of 0.22 for the case of $N=3$. This value is still less than that of Case B, while it is not always sufficiently small enough. This tendency continues as N increases, with the maximum of $|C_y - C_{ym}|$ reaching value of 0.27 for the case of $N=4$.

4) Case D; Weighted parameter by an iterative method.

Fig. 2. a)-d) Ratio of Cy to $Cym(Cy/Cym)$ for the case of $N=2$. Note that the contours are given in %. The horizontal axis indicates values of $C(\Psi_1)$, and the vertical axis indicates values of $C(\Psi_2)$. a) for Case A. b) for Case B. c) for Case C. d) for Case D. e) the value of w in Case C. f) the value of w for Case D.

Fig. 3. a)-d) Difference of Cy and Cym ($|Cy - Cym|$) for the case of $N=2$. Cases are the same as Fig. 2 a)-d). e) The value of w as an analytic solution of Eq.(9) for the case of $N=2$.

Fig. 4. a) The number of required iterative calculations to keep $|Cy - Cym|$ below a value of 0.05 when $w_0=1$ is used as the first guess value for the case of $N=2$. The horizontal axis indicates the values of $C(\Psi_1)$, and the vertical axis indicates the values of $C(\Psi_2)$. b) the same as a) but for $N=3$. The case of $C(\Psi_3)=1$ is shown as an example which maximizes $|Cy - Cym|$. c) the same as a) but for $N=4$, $C(\Psi_3)=C(\Psi_4)=1$. d) the same as a) but $w_0=1/N$ is used as the first-guess value. e) the same as b) except $w_0=1/N$ is used. f) the same as c) except $w_0=1/N$ is used.

The value of w which makes Cy equal to Cym is obtained as a solution of the following N -th order algebraic equation.

$$\frac{1}{N} \sum_{i=1}^N C(\Psi_i) = 1 - \prod_{i=1}^N (1 - wC(\Psi_i)) \quad (9)$$

Fig. 3e shows the value of w as the analytic solution of the above equation for the case of $N=2$. The value is somewhat smaller than that shown in Fig. 2e, and this value makes the difference $|Cy - Cym|$ shown in Fig. 3c.

From a practical stand point, an approximate solution which makes $|Cy - Cym|$ sufficiently small is readily available. For the case of Eq.(9), consider that the right-hand side of the equation is divisible by w , it can be rewritten as follows:

$$w = \frac{\frac{1}{N} \sum_{i=1}^N C(\Psi_i)}{\frac{1}{w} (1 - \prod_{i=1}^N (1 - wC(\Psi_i)))} \quad (10)$$

Then Eq.(10) is solved by an iterative method,

$$w_n = w_{n-1} \frac{Cym}{Cy(w_{n-1})} \quad (11)$$

where

$$Cy(w) = 1 - \prod_{i=1}^N (1 - wC(\Psi_i)) \quad (12)$$

Since the value of Cyt in Eq.(7) is equivalent to that of $Cy(1)$ in Eq.(12), the value of w derived from Eq.(7) is the same as that from the first approximate solution obtained by an iterative method for Eq.(9), when the first guess value is set to 1. Figs. 2f and 2d show the second approximate value of w and Cy/Cym when that value ($=w_2$) is used for the case of $N=2$. The value of w approaches that of the analytic solution shown in Fig. 3e compared to that of Case C, and Cy/Cym approaches value of 1. In

Table 2. The results of the comparative study of Cases A-D. The number of iterative calculations used in Case D is equal to that of levels N .

Case (Number of levels)	Assessment of C_y	Max of $ C_y - C_{ym} $		
		$N = 2$	$N = 3$	$N = 4$
A(no adjustment)	overestimate for abundant cloud	0.50	0.67	0.75
B($w = 1/N$)	underestimate for infrequent cloud	0.25	0.30	0.32
C($w = C_{ym}/C_{ys}$)	occasionally overestimate	0.09	0.22	0.27
D(iterative method)	relax the result of case C	0.05	0.07	0.08

this case, the maximum $|C_y - C_{ym}|$ is about 0.05, as shown in Fig. 3d.

Figure 4a shows the number of required iterative calculations to keep $|C_y - C_{ym}|$ below a value of 0.05 when $w_0=1$ is used for the case of $N=2$. As N increases, the number of required iterative calculations increases as shown in Figs. 4b and 4c. If $w_0=1/N$ is used as the first-guess value, the number of required iterative calculations becomes small for many combinations of the values of $C(\Psi_i)$ as shown in Figs. 4(d)–(f).

The results of these comparisons are summarized in Table 2.

5. Summary and conclusion

A comparative study of apportionment schemes for cloud amount in the radiation calculation of numerical prediction models was performed for the case that a certain diagnostic relationship between cloud amounts and several large scale variables was given. The assessment of the schemes was carried out by comparing the two-dimensional total cloud cover C_y and the averaged diagnostic cloud amount C_{ym} , with the following four cases being compared.

Case A; No adjustment, Case B; Divide by the number of levels (which had been used in the JMA's 12L-NHM up to February 1988), Case C; Weighted parameter according to the cloud amount (which is currently used in the JMA's 16L-GSM since March 1988), Case D; Weighted parameter by an iterative method.

The following results were found with respect to the above four cases.

1) C_y was overestimated in Case A. The difference $|C_y - C_{ym}|$ became exceedingly large when the number of levels was large. 2) In Case B, C_y was underestimated when the cloud amount at each level was near 1. This tendency became significant when N was large. 3) C_y was at times overestimated in Case C. This tendency increased when N was large. 4) The cloud amount was well adjusted in Case D. The required number of iterative calculations increased with the increase of N .

It was revealed that the value of w used in Case C was the same as that of the first approximate solution obtained with an iterative method for the N -th order algebraic equation when the first guess value

was set to 1 in Case D.

The study in this note was based on the assumption of random overlap in clouds, thus it is not appropriate to apply the results of this study to a numerical model which does not assume a random overlap. If random overlap is assumed and the cloud is considered blackbody in the calculation of the long wave radiative fluxes in the model, the results of this study (Case D) are available for the adjustment of the long-wave radiative quantities such as OLR to a value which is demanded from the two-dimensional cloud amount of the diagnostic relationship. For the case of the calculation of the short-wave fluxes, which deals with the optical thickness of the cloud, the validity of the results of this study will depend upon the propriety of the assumption of random overlap. Some additional adjustment to the cloud amount may be required according to the details of the radiative calculation scheme.

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診断式による雲量のモデル面への割り振り法の比較

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