# TREATMENT OF BROKEN CLOUDS IN ICM RAS ATMOSPHERIC MODEL

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*The paper presents diagnostic formulas for calculation of cloud fraction in ICM RAS GCM, together with the algorithm of calculating radiative heat influxes to atmospheric layers containing multilayer broken clouds. Model results are compared with satellite observations.*

The Institute of Computational Mathematics of Russian Academy of Sciences (ICM RAS) general circulation model (GCM) is a fully three-dimensional (3D) global model, based on the closed system of nonlinear equations of atmospheric hydrothermodynamics. The current version of the model spans the entire troposphere and stratosphere up to 50-km height, as well as a ground layer down to the depth of 10 m. The model includes all basic physical processes. Its horizontal resolution is 5° longitude by 4° latitude. Vertically, the atmosphere is divided into 21 layers, 13 of which are located in the troposphere. The ICM RAS model is well described in Ref. 1, while the radiation scheme is presented in Ref. 2. Model clouds are determined diagnostically at all tropospheric levels, and mostly they are taken to be multilayer, allowed to simultaneously occur in all tropospheric layers.

The radiative fluxes are calculated independently in each finite-difference grid cell. These cells extend hundreds of kilometers horizontally, while not exceeding atmospheric depth in vertical; thus, given that overall height of cloud formations is on the order of 10–12 km, the cells are an order of magnitude larger horizontally than vertically. Within each cell, we use the radiative transfer equation for horizontally homogeneous medium. This is done by first approximating each inhomogeneous layer, containing partial cloudiness, by homogeneous layer with the account of vertical overlap of multilayer clouds. Then, we use conventional methods of upward and downward flux calculation, and, in particular, employ the two-stream delta-Eddington approximation[2] to calculate solar radiative fluxes in an absorbing and scattering medium.

We will briefly describe the methods of cloud simulation used in the ICM RAS model. We take that $C_k$, $0 \le C_k \le 1$, denote the cloud fraction of the $k$th model layer. Cloud thickness is assumed to coincide with the geometrical thickness of the corresponding model layer, while cloud horizontal sizes are not subjected to any restrictions. Processes of cloud formation are related parametrically to convective and large-scale processes in the model.

Our model, like in Ref. 3, calculates the convective cloud amount from the intensity of convective precipitation $P_{\text{conv}}$:

$$A_{\text{conv}} \text{ a } a + b \ln(1 + P_{\text{conv}}), \tag{1}$$

where the constants $a$ a 0.2 and $b$ a 0.125 are determined by statistically analyzing the relations among the atmospheric parameters of a primary concern here. Clouds are confined in the vertical to the region of convective activity. We assume that the top and bottom boundaries of convective clouds coincide with the model levels CT and Cb, respectively. The heights of CT and Cb levels, as well as the $P_{\text{conv}}$ values, are calculated at each model time step, i.e., every hour in the present model version. We take that $A_{\text{conv}}$ represents the total (in all convective cloud layers) amount of the convective clouds in the case of random overlap of cloud layers between the CT and Cb levels. Then, the convective cloud amount $C_{\text{conv}}$ in each individual layer between the CT and Cb levels will be defined by the formula

$$m \text{ a } 1/[(\text{CB} - \text{CT}) + 1],$$
$$C_{\text{conv}} \text{ a } 1 - (1 - A_{\text{conv}})^m. \tag{2}$$

Latitudinally, this mechanism of cloud formation is generally confined to the tropical zone, where it drives the bulk of the clouds. Beyond the CT and Cb heights, $C_{\text{conv}}$ is set to zero.

The amount of large-scale clouds will be parameterized in terms of relative humidity:

$$C_{\text{large}} \text{ a } \max\left(\frac{RH - RH_{\text{cr}}}{1 - RH_{\text{cr}}}, 0\right), \tag{3}$$

where $RH$ is the relative humidity at any model level; and $RH_{\text{cr}}$ is the critical relative humidity. This linear dependence of the cloud fraction on relative humidity has been traditionally used since the earliest versions of our model; whereas in most other models currently in use the quadratic dependence has been generally assumed.

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Clouds in the ICM RAS model are allowed to occur in all tropospheric layers. High-level clouds are assumed to spread upward to 400 mbar pressure level, low-level clouds downward of 700 mbar, and medium-level clouds reside somewhere in between. At each atmospheric level there are several cloud layers. Critical relative humidity was set to 0.77, 0.75, and 0.87, respectively, for the high, medium, and low atmospheric levels; which values were obtained in the numerical experiment by comparing the observed and model cloud fields. These constants in fact represent the fit parameters in each model version, and they depend on the model resolution and assumed cloud overlap. For the three lowest model layers, within the 1-km thick boundary layer, the maximum permissible cloud fractions were additionally restricted to certain limiting values. Formulas relating the large-scale cloud processes with relative humidity generally hold true at moderate to high latitudes, while their contribution in the tropics is fairly minor. In alpine regions, the model isobars confine the cloudiness to lower altitudes than mountain peaks, so the latter may appear cloud free. The total cloud fraction for each model layer is then calculated from a combination of large-scale and convective cloud fractions as

$$C = (1 - C_{\mathrm{conv}})\, C_{\mathrm{large}} + C_{\mathrm{conv}}. \tag{4}$$

An additional prognostic variable, used in a number of current climate models, is the cloud liquid water content (LWC) $W_{\mathrm{cl}}$. In ICM RAS model, there is no yet a prognostic scheme for LWC, and it is diagnostically predicted from temperature using the formula first introduced by Mazin,[4] and then refined somewhat in Ref. 5:

$$W_{\mathrm{cl}} = 0.12669 + 6.7773 \cdot 10^{-3}\, T + 1.2937 \cdot 10^{-4}\, T^2 + 8.6684 \cdot 10^{-7}\, T^3, \tag{5}$$

where $T$ is the layer temperature in degrees Centigrade. When the layer temperature is above zero, $W_{\mathrm{cl}}$ is chosen to correspond to zero temperature, and when it is below −50°, $W_{\mathrm{cl}}$ corresponds to temperature −50°. The separation into liquid and ice phases of water at a fixed temperature $T$ is made using Matveev's formula[6]:

$$f = 0.0059 + 0.9941 \exp(-\,0.003102\, T^2), \tag{6}$$

where $f$ is the liquid-phase fraction of water, and $(1 - f)$ is the ice-phase fraction. According to this formula, unfrozen water droplets may exist at quite low temperatures in the cloud. The effective radius was assumed to be 10 μm for water droplets and 30 μm for ice particles. Liquid water path (LWP) of each layer was taken as a product of $W_{\mathrm{cl}}$ and the characteristic cloud thickness at a given atmospheric level.[7] In most atmospheric models, the cloud thickness is adjusted such that the model results agree with actually observed cloud albedo; while in ICM RAS model, it is assumed equal to the geometrical thickness $\Delta z$ of the model layer. Accordingly, the cloud LWP, $UCLD$, and IWP, $UICE$, are given as

$$UCLD = W_{\mathrm{cl}}\, f\, \Delta z,$$

$$UICE = W_{\mathrm{cl}}\, (1 - f)\, \Delta z. \tag{7}$$

We have separated the cloud water in this way in order to calculate the optical properties of the distinctly different phase components independently; the resulting LWC and IWC are assumed to be in-cloud only, rather than belonging to the entire layer where the clouds are located.

The methods of calculating cloud fractions and cloud optical properties of individual model layers are essentially irrelevant; it is only important to remember that every layer is in fact horizontally inhomogeneous. Our subsequent task will be to transform from the system of multilayer overlapping system of broken clouds, occupying much of the troposphere, to a set of horizontally homogeneous layers amenable to fast deterministic methods of radiative flux calculations. This will be done using different hypotheses of vertical cloud overlap at different atmospheric levels, namely the hypotheses of random and maximum cloud overlap. The first hypothesis assumes independent cloud distributions in different cloud layers, both at the same and different atmospheric levels; whereas the second constrains cloud positions to just one above/below another. The ICM RAS model uses a mixture of the hypotheses.

The probability $p_{nm}$ that photon encounters no cloud on a vertical path between model levels $n$ and $m$ is given as:

$$p_{nm} = g\, p_{nm}^{\max} + (1 - g)\, p_{nm}^{\mathrm{random}},$$

$$p_{nm}^{\mathrm{random}} = \prod_{k=n}^{m-1} (1 - C_k),$$

$$p_{nm}^{\max} = 1 - \max_{n \le k \le m-1} (C_k), \tag{8}$$

where the probabilities $p^{\mathrm{random}}$ and $p^{\max}$, corresponding purely to hypotheses of random and maximum overlap, are weighted by the empirical parameter $g$. The hypothesis of maximum cloud overlap (the parameter $g$ close to one) is appropriate in the tropics, whereas the hypothesis of random cloud overlap (the parameter $g$ close to zero) is usable at high latitudes. Clouds at the same model level (either high- or low-level clouds) appear to be integral parts of the same cloud system, and for them the $g$ parameter value very close to unity can be used. On the other hand, clouds at different atmospheric levels can be viewed as an ensemble of independent entities for which a near-zero $g$ value is the best choice. Theoretically and experimentally invalidated, here the parameter $g$ was determined by numerical simulation and set close to the above mentioned values.

Consider a photograph of vertical cloud arrangement. No matter which overlap hypothesis is being used, within any integration cell there may simultaneously occur clear spaces, as well as regions occupied by one-, two-,..., $n$-layer clouds. Merging together regions containing identically layered clouds, in the general case of $n$-layer cloud system we finally obtain $2^n$ of such sub-cells. For simplicity, we will consider a system of three atmospheric levels, with respective cloud fractions being $c_1^m$, $c_2^m$, and $c_3^m$. We use $p_1$ to denote the area (fractional sky coverage) for clear-sky cell, $p_2$ for a cloudy cell containing high-level clouds only, $p_3$ for mid-level clouds only, $p_4$ for low clouds only, $p_5$ for high plus mid-level clouds, $p_6$ for high plus low clouds, $p_7$ for mid-level plus low clouds, and $p_8$ for a cell containing clouds at all three levels simultaneously. In the case considered here, the number of atmospheric levels is 3, hence the total number of atmospheric cells is $2^3 = 8$.

The parameters $p_i$, $i = 1, \ldots, 8$, can be readily calculated from formula (8); for instance, if random cloud overlap is assumed for a three-layer system of three atmospheric levels, the formulas for calculating $p_i$ are as follows:

$$\begin{aligned}
p_1 &= (1 - c_1^m)(1 - c_2^m)(1 - c_3^m),\\
p_2 &= c_1^m (1 - c_2^m)(1 - c_3^m),\\
p_3 &= (1 - c_1^m)\, c_2^m (1 - c_3^m),\\
p_4 &= (1 - c_1^m)(1 - c_2^m)\, c_3^m,\\
p_5 &= c_1^m c_2^m (1 - c_3^m),\\
p_6 &= c_1^m (1 - c_2^m)\, c_3^m,\\
p_7 &= (1 - c_1^m)\, c_2^m c_3^m,\\
p_8 &= c_1^m c_2^m c_3^m.
\end{aligned} \tag{9}$$

According to the hypothesis of maximum cloud overlap, formulas (9) reduce to

$$\begin{aligned}
p_1 &= 1 - \max(c_1^m, c_2^m, c_3^m),\\
p_2 &= c_1^m - \max(c_2^m, c_3^m),\\
p_3 &= c_2^m - \max(c_1^m, c_3^m),\\
p_4 &= c_3^m - \max(c_1^m, c_2^m),\\
p_5 &= \min(c_1^m, c_2^m) - c_3^m,\\
p_6 &= \min(c_1^m, c_3^m) - c_2^m,\\
p_7 &= \min(c_2^m, c_3^m) - c_1^m,\\
p_8 &= \min(c_1^m, c_2^m, c_3^m).
\end{aligned} \tag{10}$$

Negative $p_i$ values are taken to be equal to zero, and all $p_i$ sum to unity. These formulas, in combination, can be used to treat the general case of cloudiness present at all three atmospheric levels. Actually, the first formula in (8) can now be written as

$$p_i = g\, p_i^{\max} + (1 - g)\, p_i^{\mathrm{random}}, \; i = 1, \ldots, 8. \tag{11}$$

Thus, when the parameter $g$ is known, it is possible to formalize calculation of $p_i$ for any possible cloud overlap in vertical direction. The idea behind this permutation is that each of the $2^n$ cloud configurations is homogeneous in horizontal and, thus, can be treated by deterministic radiative transfer methods through application of conventional equations of radiative transfer in a non-random medium.

To synthesize the general solution of the transfer equation in a cell, we assemble the solutions for sub-cells as $F = \Sigma p_i F_i$, where $F_i$ is any radiative property (such as flux) in the $i$th cloud configuration. Such a method is very successful for radiation calculations in the atmosphere with partial cloudiness, and gives quite satisfactory results in this case. In a more general case, the properties of the real cloudy atmosphere must be used to determine not only the trivial parameter $g$, but also the matrix of the mutual correlations between cloud layers as functions of dynamic factors. Our model assumes the simplest case outlined above, and derives $g$ from data of ERBE satellite. For consistency, we compared our model results to those obtained by other methods of generating horizontally homogeneous cells, such as the NCAR model[8] where the cell homogenizing is performed by a horizontal “spreading-out” of cloud optical density according to the formula

$$\tau_{\mathrm{cl}}^{\mathrm{eff}} = \tau_{\mathrm{cl}}\, C_k^{1+\alpha},$$

where $\tau_{\mathrm{cl}}$ is the optical thickness of clouds in the layer $k$; $\alpha$ is the smoothing parameter; and $\tau_{\mathrm{cl}}^{\mathrm{eff}}$ is the effective optical thickness of a cloud in the entire layer. Thus, the treatment of partial cloudiness simplifies to that of the overcast cloud layer with a known optical depth $\tau_{\mathrm{cl}}^{\mathrm{eff}}$. The required “spread-out” parameter is determined by numerical experiment, and is found to be 0.5 in the NCAR model. Radiative flux calculations using the method of configurations described above show better agreement with the observations than the NCAR model results.[8] For this reason, the ICM RAS model uses the method of configurations. Further, a maximum cloud overlap (the $g$ parameter strictly equal to 1) is assumed for clouds at the same atmospheric level, and a random overlap (near-zero $g$ dependent on latitude) for clouds at different atmospheric levels. At each atmospheric level, we choose the maximum cloud fraction $c_1^m$, $c_2^m$, $c_3^m$, whose value is then used to calculate the coverage $p_i$. In other layers at a given atmospheric level, with cloud fractions not always coinciding with the maximum cloud fraction mentioned above, the "spread-outB method was applied. For the case considered here, a zero smoothing parameter α was found out to be most appropriate.

An obvious method drawback is its complete neglect of any interaction between different cloud configurations. This method calculates the radiative fluxes at a small fraction (in a few fractions of a second) of cost of benchmark Monte Carlo computations; yet it well fits observational data, possibly, because of the large horizontal extension of the computation cell.

The method, outlined above and used in the ICM RAS model, was the issue I frequently discussed with G.A. Titov, who, in particular, asserted that there must exist some effective fractional coverage $p_i$ through which the interaction between cloud configurations could correctly be taken into consideration. Using these effective parameters, cloud properties could be calculated with greater realism and very efficiently, what is very important for present-day GCM radiation codes.

A detailed description of the algorithms of radiative flux calculations in the above-mentioned horizontally homogeneous layers was given in Ref. 2 and is not repeated here. As an illustration, we will compare our model results with ERBE data. As part of the AMIP II experiment, we have calculated atmospheric and oceanic parameters for the entire period from 1979 to 1996; however, satellite observations of the radiation budget components at the top of the atmosphere were made only between 1985 and 1988, which period is chosen here for comparison with ERBE data.

Figure 1 presents zonally mean clear-sky and all-sky fluxes of outgoing long-wave radiation, as well as the short-wave radiation budget at the top of the atmosphere, while Fig. 2 gives corresponding cloud radiative forcings. Model results appear to agree pretty well with the observations. The observed discrepancy in behaviors of the radiative forcings is mainly explained by the fact that model humidity fields differ from those actually observed in the atmosphere.

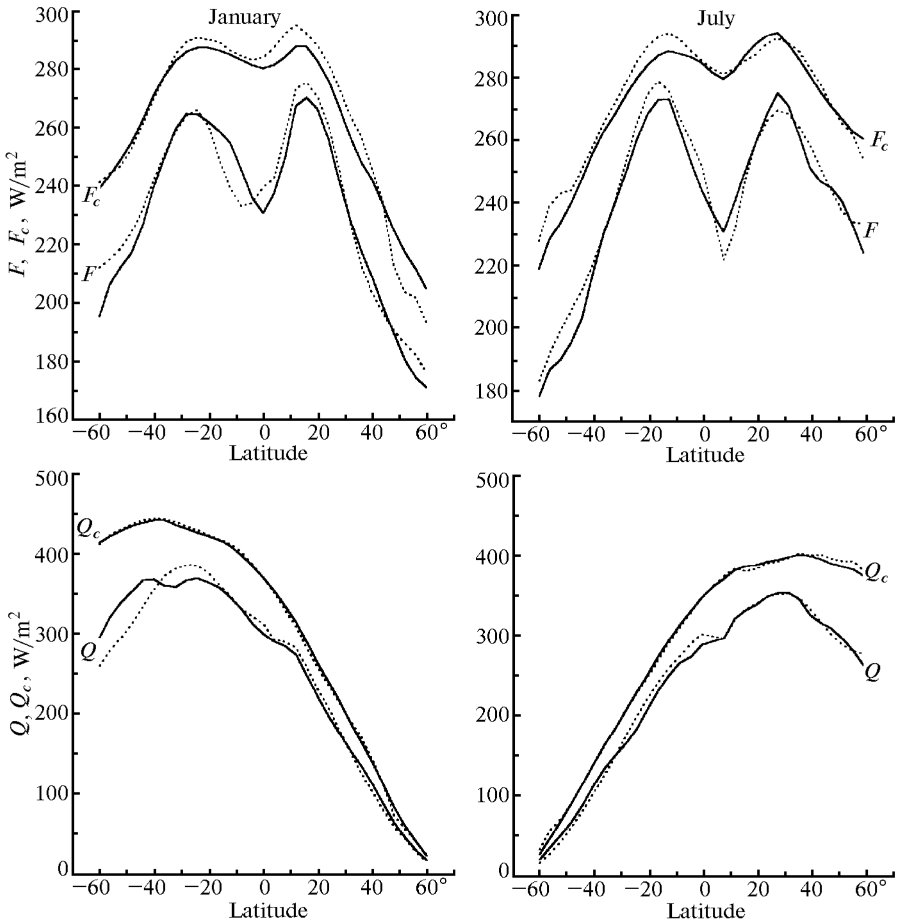


*FIG. 1. Zonally mean values of clear-sky and all-sky fluxes of outgoing long-wave radiation ($F$, $F_c$) and of short-wave radiation budget at the top of the atmosphere ($Q$, $Q_c$); solid lines show model data, and dashed lines the ERBE data for January and July.*

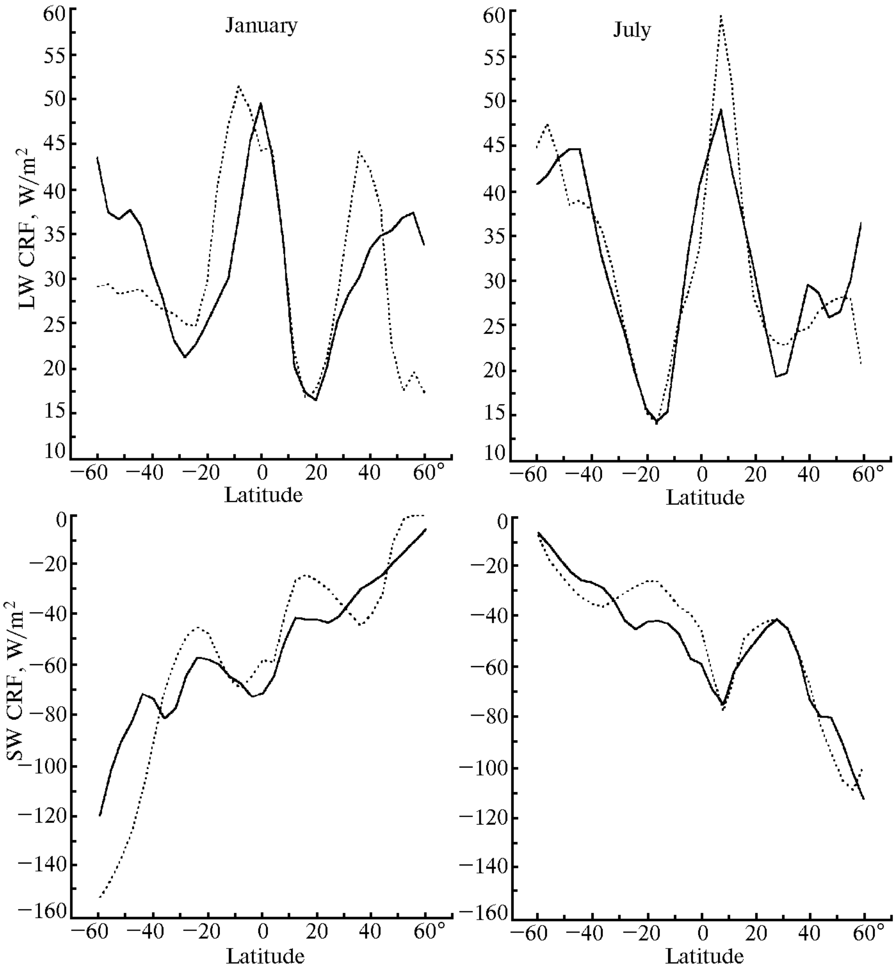


*FIG. 2. Zonally mean long-wave and short-wave cloud radiative forcings, LW CRF and SW CRF; solid lines show model data, and dashed lines the ERBE data for January and July.*

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