A STUDY OF CLOUD-SYSTEM MODEL: MACRO AND MICRO STRUCTURE SIMULATION OF CLOUD FIELD *

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ABSTRACT

The macro and micro cloud physics structures and their evolution with time are the core of describing cloud fields in essence. They are necessary atmospheric environment not only in aviation and spaceflight activities but also for atmospheric radiation transfer and acid rain formation research. Unfortunately it is difficult to obtain an entire environmental cloud field by using observation methods directly. Thus, by use of computation physics method to build a cloud-system model may be an indispensable way for this topic. This paper presented a cloud-system model for this goal, and simulated a real case. The results of computation showed that the macro structure of the cloud field was better consistent with real observation, and the micro structure was fairly reasonable. The output of model could provide all the information about the cloud field: (1) size-distribution spectrum of hydrometeor particles (point), (2) vertical profile (line), (3) horizontal or vertical section of macro and micro parameters (surface), and (4) cloud cover, pattern of cloud and configuration of cloud, etc. (body).

Key words: cloud field, simulation, macro and micro structure, cloud-system model

I. INTRODUCTION

The macro and micro structures of a cloud field are very important environment conditions. The macro structure means the three-dimensional distribution of a cloud (cloud cover and cloud thickness), cloud properties (cumuliform, stratiform and stratocumuliform), patterns and configurations (zonality, cluster-shape, wave-shape, vortex-shape and spiral-shape), etc. The micro structure of a cloud field includes the phase, specific content, specific concentration, shape and size-distribution of hydrometeor particle groups. Of course the corresponding dynamical and thermal parameters such as wind, vertical velocity, pressure, temperature and humidity of a cloud field must be given.

The task of the cloud-system model is to evaluate all the parameters as stated above and their evolution with time by use of the computation physics method and to demonstrate the spectrum of particle size-distribution at any point, the profile of water content in a line, the section of parameters along a surface, and the three-dimensional cloud field.

In recent years, the cloud field simulation study has started, e.g., Smolarkiewice and Clark (1985) and Proctor (1985) etc. However, all the work only emphasized on the macro structure of cloud and did not pay attention to the describing of the micro cloud-system structure. Thus

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it follows that the direction of cloud–system simulation study is to lay equal stress on both the macro and micro structures, to consider them as a whole and to explore the essential characteristics of the interaction between them under a given thermal–dynamical model frame for a real case. It is because that from the point of view of the macro the dominant factors controlling the cloud–system structure are the dynamical and thermal conditions which determine the formation, development, movement, maintenance and dissipation of clouds; and from the point of view of the micro the micro structure of cloud is also dependent on detailed cloud–precipitation microphysics processes. On the other hand, which of the microphysical processes can be activated and developed relies on the macro background and in turn the microphysical processes have feedback effects on the macro–scale thermal–dynamical background. Thus the model used for cloud field simulation must be an inter–coupling dynamics–cloud physics model system. This paper worked on creating a model system and made a simulation test of a real case.

II. MODEL

A cloud field refers to cloud groups or systematic clouds corresponding to a certain synoptic type. Here our interest is in the cloud–system with a scale of over 1000 km, so the hydrostatic model can be used to provide the thermal–dynamical frame of a cloud field. The corresponding microphysics cloud model must include an explicit scheme, must be suitable for demonstrating the cloud field, and have a good function of describing the evolution of micro structures of hydrometeor particles.

On the basis of the previous principles of model design the NCAR / PSU MM4 model (Anthes et al. 1987) was used as dynamical frame. In order to suit the meteorological data set and computers used in China the data input of model and preprocess system (e.g., the selection of observation data, objective analysis, and initialization) had been modified (Xu et al. 1987) because some of them entirely depended on specific computers. In addition the explicit microphysical scheme included in MM4 may be simpler. We should like to design a more detailed one (M91). This model is called as NCAR / PSU / MSC (MSC means Modified to Suit Chinese Conditions).

Of the cloud physics models there are various sorts. The question is how to build a model to consist with the characteristics of dynamical frame chosen. To sum up, the design of cloud model should consider the following:

(1) For the processes concerning water phase change, it is necessary to make efforts to be perfect and accurate. The transformations between water substances should be closed and conservative. Because these are the main channel of interaction between the cloud physics model and synoptic dynamical model.

(2) The single–parameter scheme describing the evolution of size–distribution of hydrometeor particles may cause obvious mistakes (Xu and Wang 1985a), and the mass–categorical stochastic scheme is too complex to use in the study of cloud fields. Neither is suitable. Comparatively, the bi–parameter scheme is appropriate.

(3) The hailstones in cloud are high fall speed particles, and the growth and maintenance of which in clouds require a strong updraft airflow to support. Furthermore the spacial scale of hailfall is about 10 km, often less than the grid size, and the hailfall belongs to a small–probability event. Therefore the hailfall is a subgrid phenomenon and can be ignorable.

(4) Because of the hail being removed the maximum size of graupel can be extended to an

enough scale. Thus the difference of size–distribution range between the snow graupel and frozen–rain graupel is small and ignorable, and then the corresponding aerodynamical difference is also vanished. Under this consideration the two kinds of graupels can be replaced by single one. Therefore the solid phase precipitation particles only include snow and graupel particles.

(5) According to the definitions, the lower scale limits of rain and snow particles are 200—300 microns, and for graupel it is about 1000 microns. Accepting this limitation would cause much trouble in detail computation. For this reason it is suggested that the size–distribution ranges of all the hydrometeor particles should range from 0 to ∞. Although this treatment may cause unreasonable overlay, e.g., outside the lower limit, the size of rain or graupel may be the same as that of droplet, we consider that the intercept of rain or snow is much less than that of cloud droplet or ice, so the error from overlay is acceptable. This approximation makes the computation of cloud physics processes considerably simplified, and makes it possible to complete the coupling of dynamical model with cloud model.

For the above mentioned five points, we have designed the M91 model which included three phases, five sorts of hydrometeors (cloud water, cloud ice, snow, rain and graupel) and 36 sorts of microphysical processes. Under the same physics frame, the model has single–parameter and bi–parameter evolution of size–distribution schemes, and can describe cumulus cloud or / and stratiform cloud. This model system may be convenient for various simulation tests.

Except for vapor, the size–distributions of the five sorts of hydrometeors were defined as follows.

cloud droplet: Its size–distribution was dependent on the activity of cloud nuclei spectrum. At present there are not enough data in this aspect and its description can be simplified with only specific concentration (A_{nc}) and variance (DR) of size–distribution given. In order to reflect A_{nc} change with cloud water specific content, A_{nc} and Q_c satisfied the following equation:

$$A_{nc} = A_{nc0} \times \frac{Q_c}{Q_{c0}},$$

where A_{nc0} and Q_{c0} were the given values.

cloud ice: $N_i(D)\mathrm{d}D = N_{0i} D^2 \exp(-\lambda_{i0})\mathrm{d}D$.

rain: $N_r(D)\mathrm{d}D = N_{0r} \exp(-\lambda_r D)\mathrm{d}D$.

snow: $N_s(D)\mathrm{d}D = N_{0s} \exp(-\lambda_s D)\mathrm{d}D$.

frozen rain: $N_f(D)\mathrm{d}D = N_{0f} \exp(-\lambda_f D)\mathrm{d}D$.

Figure 1 shows the block diagram of generation and conversion of six sorts of hydrometeors in three phases. The meanings of these Arabic numerals are as follows: (1) the conversion between vapor and cloud water PMC (quantity); (2) the auto–conversion of rain water from cloud water PMCR (Q: quantity), PNCR (N: number); (3) the frozen rain from rain PMFR (Q), PNFR (N); (4) the cloud ice generated from vapor sublimation on activated ice PMI (Q), PNI (N); (5) the auto–conversion of snow from ice PMIS (Q), PNIS (N); (6) the sublimation growth of cloud ice PMIG (Q); (7) the sublimation growth of snow PMSG (Q); (8) the evaporation of rain PRE (Q); (9) the accretion of cloud water by rain water PMRC (Q); (10) the accretion of rain by frozen rain PMFR (Q), PNFR (N); (11) the accretion of cloud ice by rain forming frozen rain PMRI (*Q*), PNRI (*N*) and decrease of ice PMRII (*Q*), PNRII (*N*); (12) the accretion of cloud ice by frozen rain PMFC (*Q*); (13) the aggregation of cloud ice by snow PMSI (*Q*), PNSI (*N*); (14) the accretion of rain by snow forming frozen rain PMSR (*Q*), PNSR (*N*) and snow concentration decreasing PNRS (*N*); (15) the accretion of cloud water by snow PMSC (*Q*); (16) the accretion of cloud water by ice PMCI (*Q*); (17) the frozen rain melting PMMF (*Q*), PNMF (*N*); (18) the snow melting PMMS (*Q*), PNMS (*N*); (19) the rain collision PNRR (*N*); (20) the snow aggregation PNSS (*N*); (21) the criterion of wet growth in snow accreting rain PMS (*Q*); (22) the criterion of wet growth in frozen rain accreting rain PMR (*Q*); (23) the criterion of wet growth in rain accreting ice PMR (*Q*). There were 36 physical processes in all. For the expressions of these generation terms readers are also referred to the method derivation described in researches of Xu (1992) and Xu and Wang (1985b). The equations are omitted here.

NCAR / PSU dynamical model and M91 cloud physics model constituted our model system.

The simulated domain of cloud–system model was large up to thousands of kilometers. Because of computation quantity limitation, we used the hydrostatic model and because of grid length could not be below 10 km, we chose a grid length of 45 km. So in treatment of cloud processes there were some physical problems in using explicit scheme to describe the interaction of cloud and environment (Molinari and Dudek 1990). Its essence was that at this time the formation and development of cloud could be handled only by average ascending motion in grid range; the average value could be significantly different from actual anaflow effect; it caused insufficient description of cumulus and its effects. In order to make up this insufficiency, we used the implicit cumulus parameterization scheme (Anthes 1977) as well. This was the so–called hybrid scheme. In this paper, for the atmospheric column with unstable stratification, when there was vapor convergence, cumulus convection was thought to occur with vapor

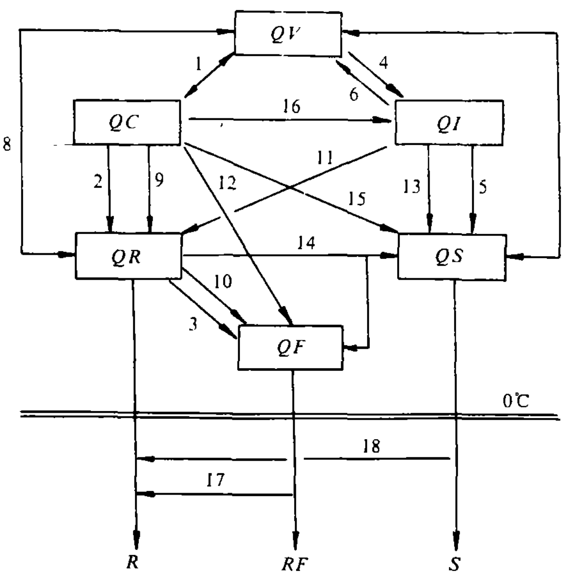

Fig. 1. Sketch of formation and conversion of 5 sorts hydrometeor particles in 3 phases. *QV*: vapour; *QC*: cloud water; *QI*: cloud ice; *QR*: rain; *QS*: snow; *QF*: frozen rain; *R*: precipitation of rain; *S*: precipitation of snow; *RF*: precipitation of frozen rain.

condensation, heating and moistening, but the water remained in the sky to participate in the explicitly described cloud physics processes (Ding 1992).

In order to show the simulation results in terms of configuration products, we designed a set of data treatment and plot packages. They could give the structural figures displaying the cloud field structure at any selected point, line or surface, and could give all the three–dimensional distribution figures in the direction of any view angle.

III. SIMULATION CASE

The chosen case was a regional heavy rain process occurred in Beijing–Tianjin–Hebei region during 26—27 June 1986. Its distinguishing feature was that the north–west eddy and the south–west eddy had linked together and interacted in the same longitude. Linkage of the eddies formed a warm–wet air transport zone reaching North China with the length being thousands of kilometers. Southward cold–dry air inducted by the north–west eddy brought about the

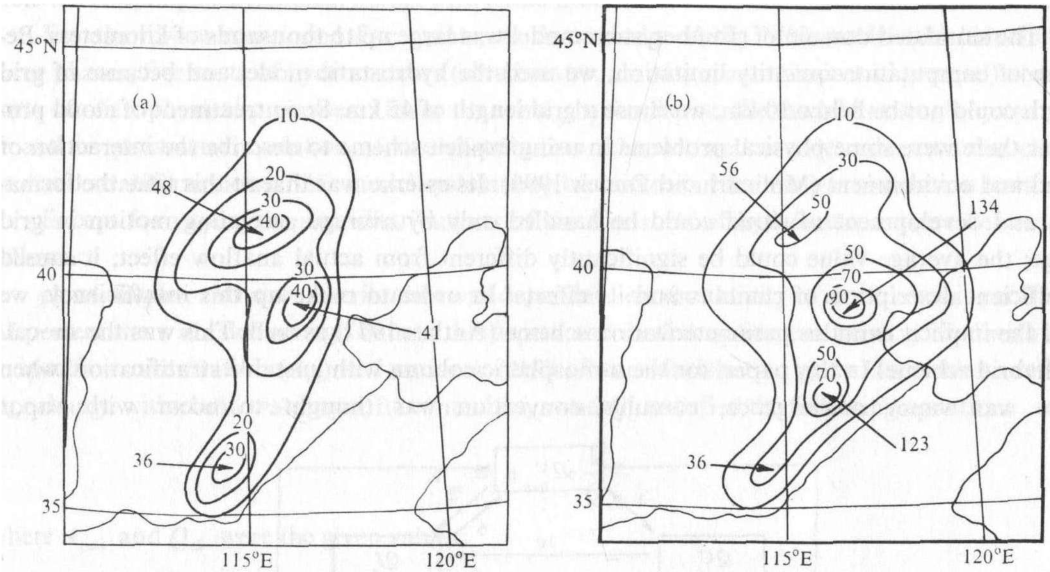

Fig. 2. The distribution of precipitation during 1200—2400 Z, 26 June 1986 for (a) the 6th hour and (b) the 12th hour.

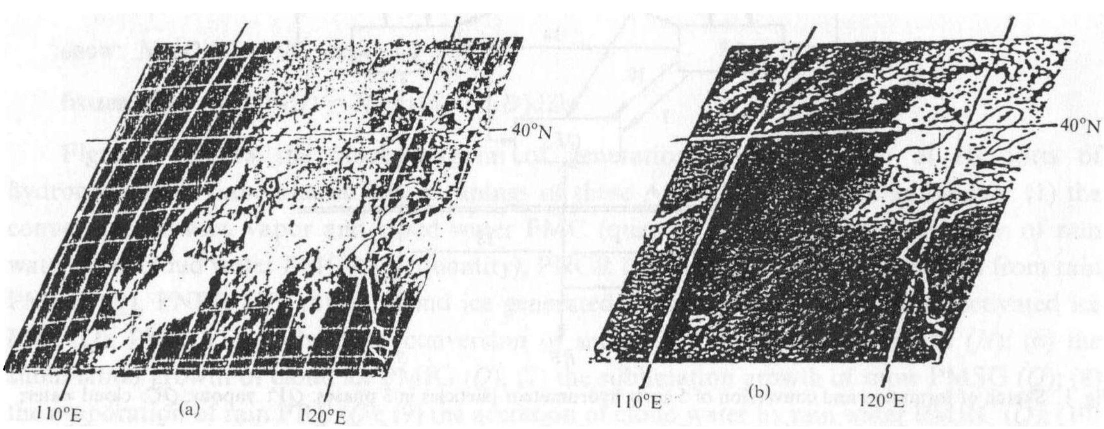

Fig. 3. The cloud images at 1200 Z (a) and at 2100 Z (b), 26 June 1986.

south–west eddy's baroclinic development, in addition the vertical couple of high–level jet and low–level jet impelled a North China mesoscale disturbance to develop (Wu 1989).

The 12–h precipitation and cloud images of this process at two time levels are given in Figs. 2 and 3.

Using the conventional synoptic data at 1200 Z on 26 June 1986, the obtained initial fields through objective analysis and initialization by removed the vertically integrated mean divergence were input to the model. The model was run for 12 hours with output computation results for each hour. The computation area was 1350 km × 1350 km with the center at (38°N, 117°E); the grid length was 45 km and there were 10 levels in the vertical direction.

IV. SIMULATION TEST RESULTS

(1) In order to examine the model capability, we compared the simulated precipitation at the 6th and the 12th hour (Fig. 4) with the observed precipitation (Fig. 2). We can see that in view of precipitation distribution, orientation of the rain band or the value of precipitation, they are all fairly identical.

(2) The simulation results of cloud fields are shown in Fig. 5. Since the initial value of hydrometeor was zero, the formation and development processes of the cloud–system needed some time. Compared to Fig. 3 the cloud field given after the model running for three hours fairly approached to the observed image in Fig. 3a. They were similar not only in the cloud distribution but also in cloud pattern. It can be seen that the main characteristics of real clouds in the north–east quadrant of the sky were stratiform, and the south–west quadrant were convective. The simulated cloud field displayed these characteristics too. Comparing the cloud field at the 9th hour with the real cloud, the cloud field had moved to the north–east corner; their cloud pattern was stratiform; and their basic characteristics were identical.

(3) The three–dimensional cloud field could only provide the macro state of clouds, such as cloud cover, cloud distribution, cloud pattern, etc. The objective image of cloud thickness was not clear. The distribution structures of the various variables and hydrometeors in clouds could

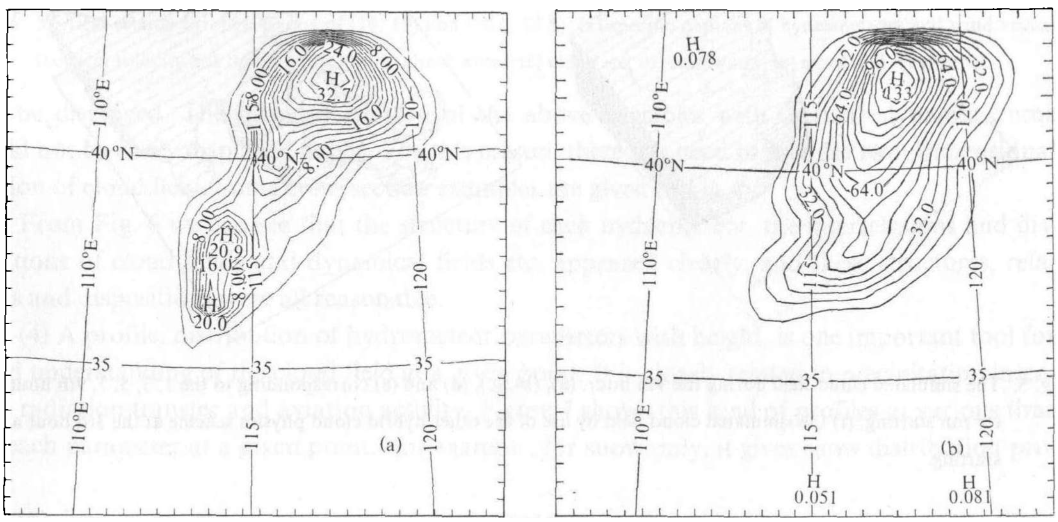

Fig. 4. The distribution of simulated precipitation for (a) the 6th hour and (b) the 12th hour.

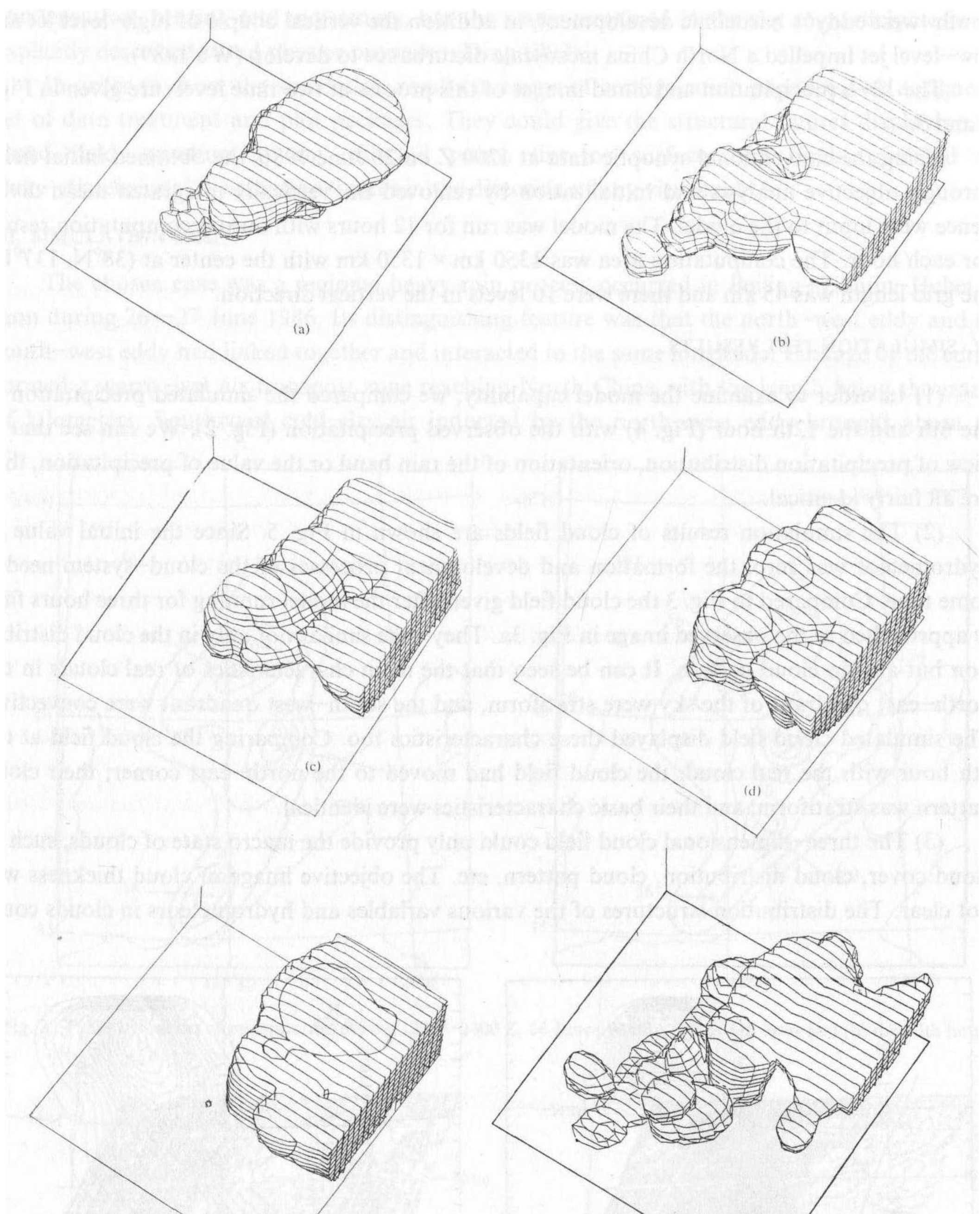

Fig. 5. The simulated cloud field during the 9th hour. (a), (b), (c), (d) and (e) corresponding to the 1, 3, 5, 7, 9th hour after run starting; (f) the simulated cloud field by use of the other hybrid cloud physics scheme at the 3rd hour after starting.

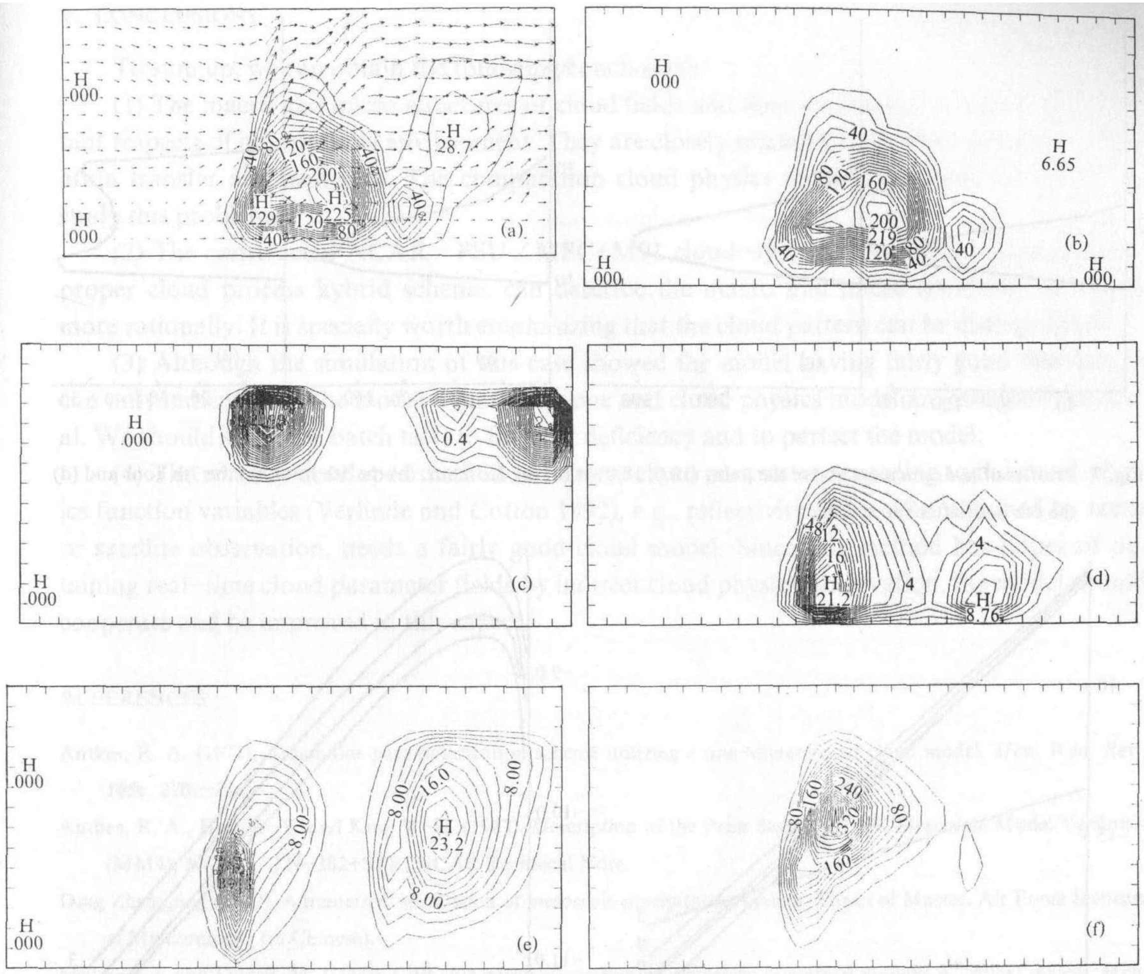

Fig. 6. Vertical section through points of (10, 10) and (30.0, 29.8). (a) specific content of hydrometeors and wind vector (vertical velocity has timed by 1000); (b) cloud water; (c) cloud ice; (d) rain water; (e) snow and (f) graupel.

not be displayed. The disposal relation of the above variables with thermal–dynamic frame could not be easily displayed either. For this reason, there is a need to give the two–dimensional section of cloud field. Some cross section examples are given in Fig. 6.

From Fig. 6 we can see that the structure of each hydrometeor, the interrelations and dispositions of cloud fields and dynamical fields etc. appeared clearly, and these structures, relations and dispositions were all reasonable.

(4) A profile, distribution of hydrometeor parameters with height, is one important tool for good understanding of the cloud field at a given point. It is closely related to precipitation intensity, radiation transfer and aviation activity. Figure 7 shows this kind of profiles at various time for each parameter at a given point. For example, for snow only, it gives snow distribution profiles.

(5) The main micro structure of hydrometeors is size–distribution of particles. Once

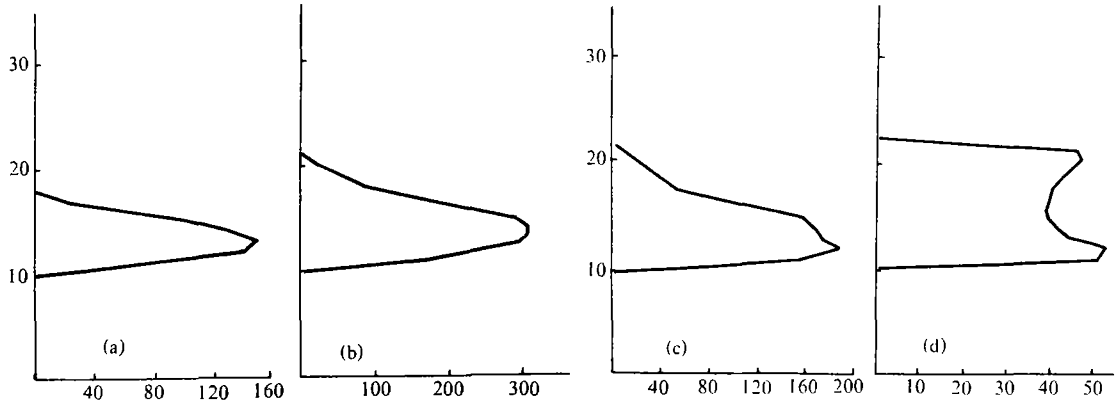

Fig. 7. Profiles of hydrometeors above the point (18.0, 18.0) at (a) the 3rd hour, (b) the 5th hour, (c) the 7th hour and (d) the 9th hour after run starting.

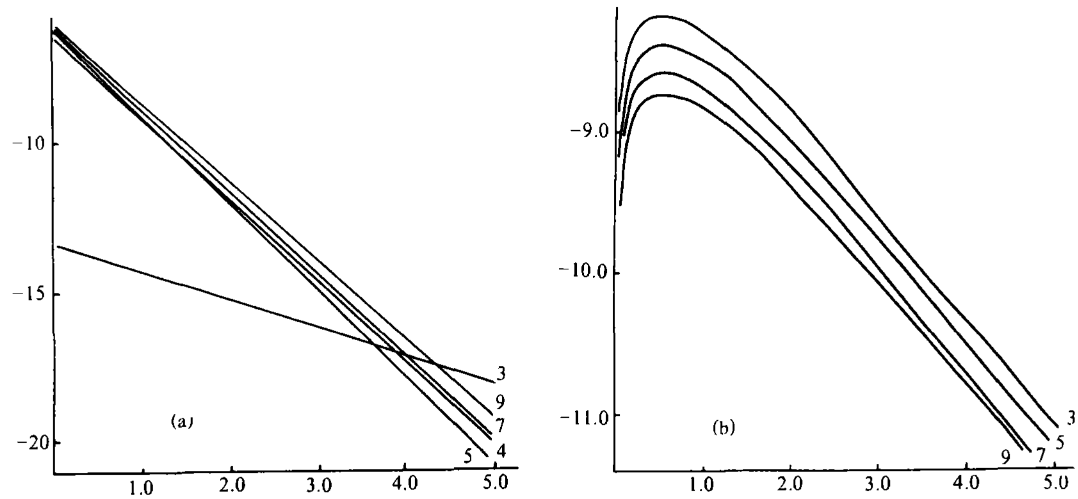

Fig. 8. Size–distribution spectrum of (a) rain and (b) snow at different levels (shown by the numbers on end of line) above the point (18.0, 18.0).

this distribution spectrum was obtained, any relative microphysical parameter could be got such as dominant diameter, median diameter, scattering cross–section, equivalent reflecting (DBZ), water content, the aerodynamic characteristics of the particles, etc. For this purpose, the distribution spectrum of different types of particles at every point in cloud needed to be given. Figure 8 shows the rain and snow particle distribution spectrums at different height levels at a point of (18, 18). Since our cloud model employed the bi–parameter spectrum evolution scheme, at different levels the given spectrum pattern not only had slope variation but also had intercept variation. The observed spectrum variation appeared so. This is the significant improvement on the single–parameter evolution scheme. If spectrum distribution differences between different points could be reflected, of course, the evolution with time of cloud spectrum of particles at the same point could be described. Because of the limited paper length, only the necessary example charts can be given here.

V. CONCLUSIONS

To sum up, we can obtain the following conclusions:

(1) The macro and micro structures of cloud fields and their evolution with time are important respects of atmospheric environment. They are closely related to aviation, spaceflight, radiation transfer and acid rain. The computation cloud physics method possesses the ability to study this problem.

(2) The constructed NCAR / PSU / MSC+M91 cloud–system model, in conjunction with proper cloud process hybrid scheme, can describe the macro and micro structures of clouds more rationally. It is specially worth emphasizing that the cloud pattern can be distinguished.

(3) Although the simulation of this case showed the model having fairly good function, it can only indicate that the model dynamics frame and cloud physics model are essentially rational. We should strive for batch tests to find out deficiency and to perfect the model.

(4) The recently developed method to retrieve cloud parameter according to the cloud physics function variables (Verlinde and Cotton 1992), e.g., reflectivity factor dBz, obtained by radar or satellite observation, needs a fairly good cloud model. Since this method has hopes of obtaining real–time cloud parameter fields by indirect cloud physics observation, the model should cooperate and be improved in this aspect.

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