Characterization of Cloud Microstructure as a Medium for Radiative Transfer

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Introduction

Measurements show that a significant amount of ice often is present in low and midlevel clouds that are only slightly supercooled. Number concentrations of ice particles as high as 100 to 1000 per liter have been observed in shallow stratiform and small cumulus clouds with cloud top temperatures as cold as -15° C and often as warm as -5° C.

The presence of an ice phase may significantly change cloud impact on radiation. In order to describe this impact correctly, knowledge of cloud microphysics is crucial.

A study that we are reporting here provides information about the microstructure of a glaciating cumulus cloud based on results from a numerical simulation. Later, cloud characteristics obtained here will be used to evaluate the effects of ice phase on the optical and radiative properties of low and midlevel clouds.

Numerical Model

In this paper, we present the results of a recently developed three-dimensional cloud scale numerical model (Ovtchinnikov et al. 1995). The model combines the non-hydrostatic dynamical framework of Kogan (1991) with the explicit formulation of ice and liquid phase microphysics. The microphysical processes of nucleation, diffusional growth/evaporation, freezing/melting, and coalescence are formulated based on the prediction equations for spectra for cloud condensation nuclei, cloud and raindrops, and ice particles. All basic mechanisms of ice nucleation are considered in the model including activation of immersion-freezing, deposition or condensation-freezing, and contact-freezing ice nuclei (scavenging model). The process of secondary ice crystal production during riming of ice particles, known as the Hallett-Mossop (1974) riming-splintering mechanism, is also included in the model.

Special attention is given to the initialization procedure to ensure that the model generates a cloud with realistic geometry and dynamical parameters. Initial perturbations in temperature and moisture fields contained both deterministic and random parts, with the scale and intensity of the thermal specified based on boundary layer similarity. In this particular simulation, the initial environmental conditions are set by the sounding constructed primarily from aircraft observations in the vicinity of the cloud that developed over the Magdalena Mountains on 9 August 1987. The flight of the National Center for Atmospheric Research's King Air airplane was part of an extensive experiment aimed at investigating the development of cloud particles in New Mexican summertime cumulus clouds. Detailed information about the field project was reported by Blyth and Latham (1993).

A uniform grid spacing of 100 m was used throughout the domain 7.5 × 7.5 × 7.5 km^3. A time step of 5 s was used in dynamical calculations, while a smaller step of 0.2 s was used in microphysical calculations.

Results

A general view of the simulated cloud is shown in Figure 1. While we cannot expect the simulated and observed clouds to be identical, it is important that the model closely reproduce the measured bulk properties. The comparison of the characteristic features of the simulated and observed clouds is presented in Table 1.

The simulated cloud-top and cloud-base heights and the maximum cloud width closely match the observations. The somewhat large difference in maximum values of liquid water content (LWC) might be expected, taking into account the incomplete sampling of the cloud by the aircraft. The aircraft was likely to miss regions of the least diluted cloud-base air. In addition, the upper portion of the cloud was not sampled; the highest penetration was at the level of about 4.3 km,

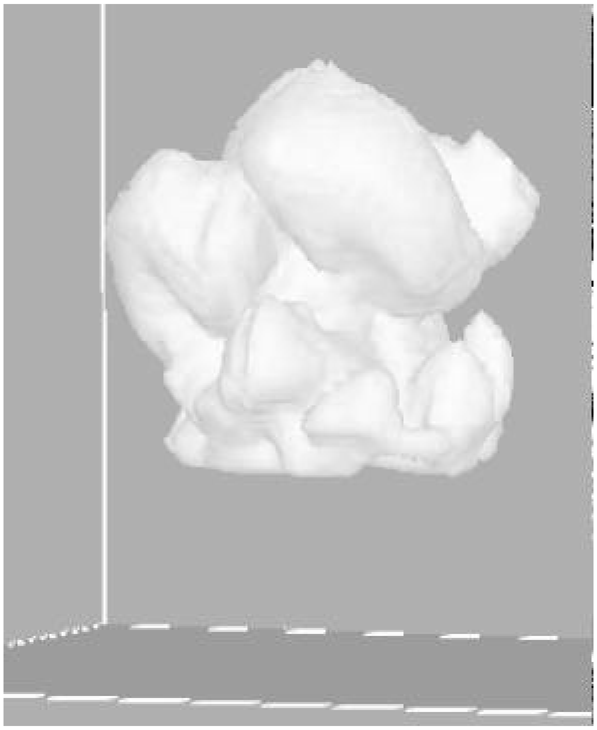

Figure 1. Isosurface of liquid water content of 0.001 g m^{-3} at 20 min. Cloud base and cloud top are at 1.8 and 5.4 km, respectively.

Table 1. Simulated vs. observed cloud properties.

Properties	Observed	Simulated
Cloud base alt. AGL (km)	1.7	1.8
Cloud base temp. (°C)	7.4	7.3
Max. cloud-top alt. (km)	5.7[(a)]	5.6
Min. cloud-top temp. (°C)	-15[(a)]	-13.8
Max. cloud width (km)	4.5	4.1
Max. vert. vel. (m s^{-1})	11.5	12.9
Min. vert vel. (m s^{-1})	-6.0	-5.5
Max. LWC (g m^{-3})	2.5	4.2
Max. cloud drop concentration (cm^{-3})	597	892
Max. ice particle concentration (L^{-1})	38[(b)]	52

(a) Estimate.
(b) Derived from the 2DC probe.

more than 1 km below cloud top. For the same reason (scarcity of observations) the model data would be expected to have greater values of the vertical velocity, concentrations of cloud drops, and ice particles, etc. Also, as noted by Blyth and Latham (1993), actual ice particle concentrations are presumably higher than the reported values derived solely from the 2DC probe. Since this probe is unable to resolve particles smaller than 25 µm, a large number of small ice crystals (splinters) may remain undetected.

The time evolutions of maximum cloud drop (CD) and ice particle (IP) concentrations are shown in Figure 2. The dashed curve in this figure reveals two distinct stages of ice production, each dominated by a different process. The first increase in the number of IPs between 10 and 15 min is due to the activation of the ice nucleus, while the second, much stronger, peak between 20 and 30 min is a result of the Hallett-Mossop mechanism (1974).

At 15 min into the simulation, as the cloud top ascends to its highest level, the maximum IP concentration reaches the value of about 4 L^{-1} (Figure 2, dashed curve). After that, the nucleation of new ice crystals weakens due to the decreasing updraft and subsequent decrease in supersaturation. The next stage of cloud evolution is very important in ice development, even though the maximum IP concentration remains nearly constant, or even decreases slightly during this period. After the small pristine ice crystals are formed, they begin to grow, mostly through deposition of water vapor. Because of the small sedimentation velocity, these particles are carried along

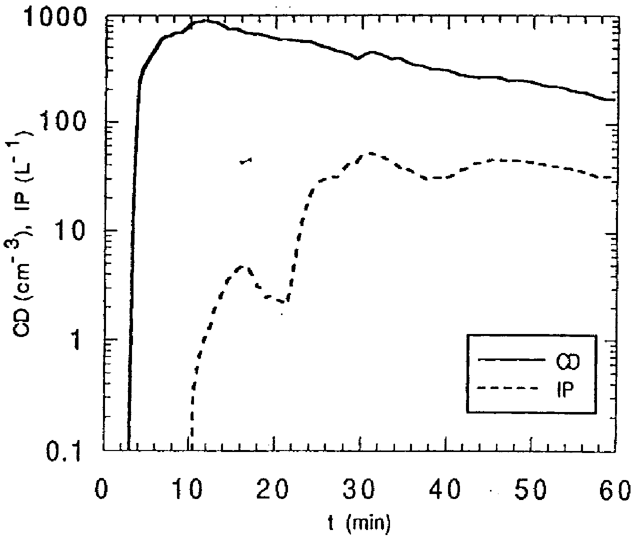

Figure 2. Time evolution of maximum cloud drop (CD) and ice particle (IP) concentrations.

with the flow from the region of their formation in the upper portion of the cloud towards cloud edges. Downdrafts therefore play a crucial role in transporting IPs to the regions where they will grow by riming and may ignite the H-M process.

The use of detailed microphysics allows us to look closely at the transformation of the cloud particle spectra. From this analysis, it appears that by the time the H-M starts, precipitation-size drops already exist in the cloud. The freezing of these drops and their conversion to graupel speeds up the multiplication process by producing new riming centers in shorter time than through diffusional growth of pristine ice crystals.

Figure 3 illustrates the transformation of the cloud particle spectra at one particular grid point where high concentrations of ice particles appear in about 10 min. At time t = 20 min, there are very few (on the order of 1 m^{-3}) ice particles. Most of these are vapor-grown crystals from activated deposition and/or condensation-freezing ice nuclei, although a small fraction may have been originated from frozen droplets via contact nucleation. The concentration of drizzle-size drops does not exceed a few per liter at this time. The number of these drops, however, increases rapidly as the collection growth progresses. In only 5 min, the concentration of drops greater than 100 µm in diameter increases by almost an order of magnitude (Figure 3). An increase in concentration of larger drops is even greater and probably more important.

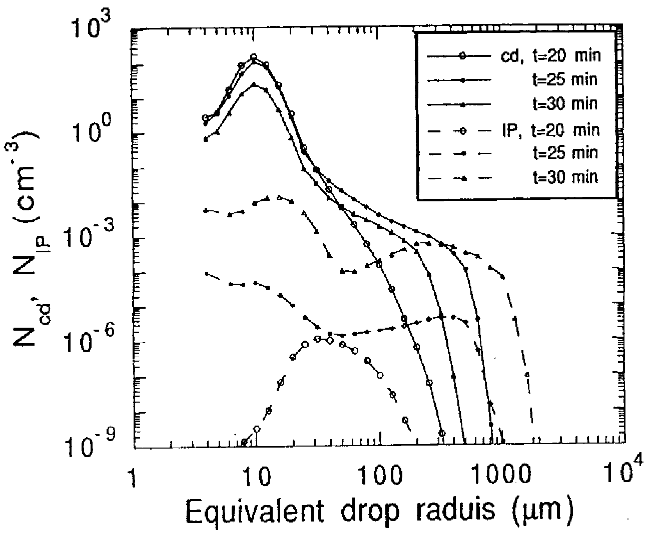

Figure 3. Size distribution functions for cloud drops (solid) and for ice particles (dashed) at one grid point at about -5° C level.

It has to be understood that the spectra shown in Figure 3, being taken at a particular grid point, are not related to any closed parcel. The time evolution of these spectra is thus a result not only of microphysical but also of dynamical processes such as advection an turbulent mixing. For instance, the difference in terminal velocities between cloud droplets and drizzle or raindrops will result in their vertical separation of hundreds of meters over a 5-min period.

Conclusions

The newly developed three-dimensional numerical cloud model is shown to reproduce well both dynamical and microphysical properties of a mixed-phase cloud of moderate vertical extent. The model provides detailed information about cloud drop and ice particle size distribution. This information may serve as input for radiative transfer models. A realistic three-dimensional structure of simulated clouds can be applied to studying, for example, the effects of clouds of finite dimensions.

Acknowledgments

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