A Model of the Microphysical Evolution of a Cloud

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The earth's weather and climate are influenced strongly by phenomena associated with clouds. Therefore, a general circulation model (GCM) that models the evolution of weather and climate must include an accurate physical model of the clouds. This paper describes our efforts to develop a suitable cloud model. It concentrates on the microphysical processes that determine the evolution of droplet and ice crystal size distributions, precipitation rates, total and condensed water content, and radiative extinction coefficients.

We assume a fixed temperature, a cloud vertical thickness, and concentrations and size distributions of cloud condensation nuclei (CCN) and ice condensation nuclei (ICN). The computation starts at time $t = 0$ with a given concentration of precipitable water entirely in the form of vapor. As time advances, we compute the evolution of the number and size distributions of the liquid droplets and ice crystals along with their evaporation/condensation rates, collision rates, vertical falling rates, and rates of loss from outfluxing. We then compute the resulting evolution of the cloud water vapor, liquid and ice concentrations. As a byproduct, the precipitation rate and the cloud optical extinction coefficient are computed.

The evaporation/condensation rate expression for liquid drops is based on the well-known Kohler equations, which include the effects of vapor pressure reduction due to dissolved CCN material (Raoult's law) and enhancement due to droplet surface tension (Gibbs-Thomson effect). An inference from these equations is that for small positive values of the vapor phase supersaturation, there is a limited range of CCN masses for which equilibrium between the liquid droplets and the vapor phase can exist. For larger CCN mass above a certain value, m_{CNcrit}, and corresponding droplet radii above the value r_{crit}, no equilibria are possible, and the droplets tend to grow without limit—until the vapor phase supersaturation is reduced.

Even in the absence of ICN or ice crystals, these equations describe a surprisingly complex range of phenomena. For a given initial value of the vapor-phase supersaturation s greater than zero (relative to liquid water), the smallest droplets tend to grow faster than the larger ones, leading to a droplet size distribution function that evolves rapidly toward a delta function—i.e., a single droplet size, until continued condensation onto the droplets causes the supersaturation to drop to a point where r_{crit}, which varies as $1/s$, increases to a value larger than the prevailing droplet radius. At that point, some of the droplets begin to reevaporate—the smallest first, causing the small drop-size (haze) part of the distribution to be repopulated. (See Figure 1.) At the same time, the largest droplets are falling more rapidly than the smaller ones, resulting in collisions and coalescence which accelerate the growth of the large drops at the expense of the smaller ones.

Figure 1 shows the computed evolution of the droplet size distribution function $dN_{drops}/d\log r$ vs r for a sequence of times for a system with only liquid water and vapor (with $T = 270$ K and an initial saturation ratio of 1.255). Condensation onto the CCN is essentially complete within about 5 seconds. The subsequent evolution is dominated by droplet coalescence and reevaporation.

A quantity of particular interest is the computed precipitation rate and the associated rate of water loss from the cloud. The computed rate of development of precipitation in clouds that include only liquid water with no ice phase is quite slow—somewhat slower than the observed rate of evolution of clouds over land. For a more realistic representation of terrestrial cloud systems, the ice phase must be included.

With the inclusion of ice, at temperatures below about 266 K, we obtain a more rapid development of precipitation (Bergeron-Findeisen effect). Because the ice crystals have

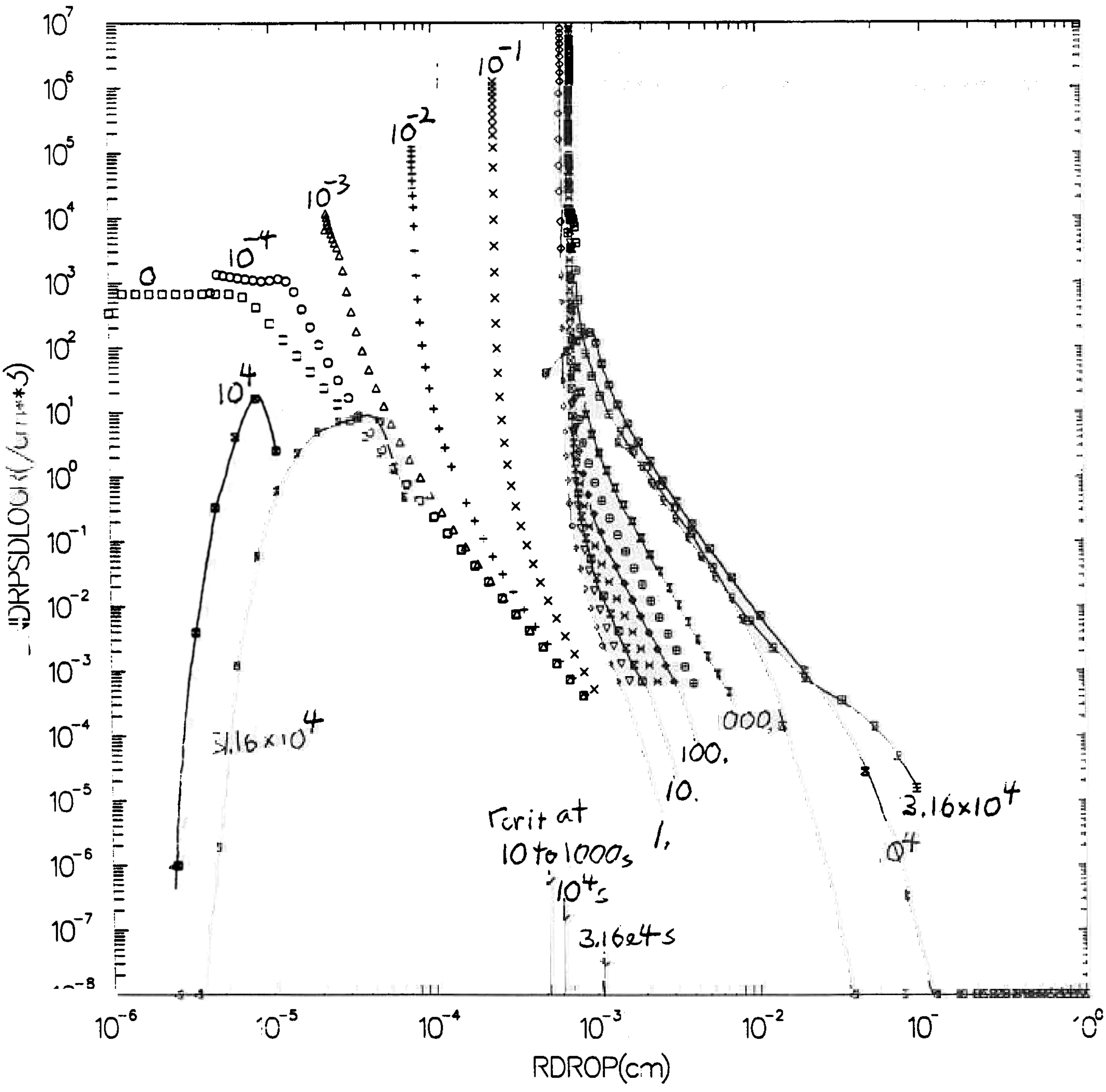

Figure 1. Liquid drop number density vs log-radius distribution function $dN/d\log r$ (cm^3) vs $\log r$ for a cloud at 270 K with no ice condensation nuclei—for a sequence of times from zero to 3.162 x 10^4 s. The times are indicated on the curves. Also shown along the r axis are the Kohler critical droplet radii at selected times. The initial water vapor concentration in this case was 1.255 times the concentration of saturated vapor.

lower equilibrium vapor pressures than the liquid water drops, water tends to evaporate off the liquid drops and condense on the ice crystals, causing the latter to grow rapidly. As the ice crystals grow, they fall with increasing speed, coalescing with liquid drops in an accelerating rate. In this model, coalescence between an ice crystal and a liquid drop is assumed to result in a larger ice crystal, with the mass of the two particles combined.

Figures 2a and 2b show the computed evolution of the droplet size distribution function and the ice crystal size distribution function when both liquid and ice are included and the initial supersaturation is quite large (T = 264 K, initial saturation ratio 1.915). Here again, condensation onto the liquid droplets is essentially complete after 5 seconds. For the next half hour, the dominant process is growth of the ice crystals by condensation and coalescence with liquid drops at the expense of the liquid drops. During the succeeding half hour, there is very rapid growth of the ice crystals and strong precipitation, resulting in substantial drying out of the cloud. For the next 8 hours, the cloud continues to evolve, with continuing precipitation and with the total number of droplets decreasing continually because of coalescence.

During most of the cloud's life, from 10 to 10^4 s the predominant liquid drop radius is 10 µm, as is typical in real clouds. The ice crystals grow steadily for the first half hour, reaching a radius of 1.4 mm, at which point they are precipitating rapidly.

Over the 8-hour period of the computation, the droplet number density drops from an initial value of about 600 per cm^3 to a final value of 3 per cm^3. The ice crystal density is about 1.3 per cm. The optical extinction coefficient drops gradually over a 9-hour period to 1.9×10^{-5} cm^{-1}.

In a real cloud, of course, we never observe a state consisting of dry CCN and highly supersaturated water vapor. In the model, this hypothetical state is simply an artificial reference point from which we start the computation. The computations show that by condensation of liquid water onto the CCN, the system evolves into a fairly realistic state within 3 to 10 seconds. After that, the initial liquid-vapor equilibration is essentially complete, and the supersaturation is reduced to between 0.01% to 0.02%. For comparisons with real clouds the initial 10 seconds of the computation should be ignored.

These computed results depend, of course, on the assumed concentration and size distribution of CCN and ICN. The distributions that we use in this model are analytic fits to data quoted by Pruppacher and Klett (1978). The effective ICN concentration is a very strong function of the degree of supercooling. We have performed parameter studies in which we vary the CCN or ICN concentrations by a factor of 10 above or below the assumed standard concentrations, or alternatively, where we set the ICN concentration to zero. The model also assumes an idealized uniform cloud of fixed vertical extent. We have also done some parameter studies with varying the vertical extent.

These computations were intended to provide a basis for developing parameterized descriptions of clouds and precipitation for use in a GCM. We have not yet finished this task. Even within the context of this idealized model, the variable parameters include temperature (T), CCN concentration, ICN concentration, cloud vertical thickness, initial saturation ratio (S^0), and time (t).

So far, only a few useful generalizations are evident. There are three distinct classes of systems to be considered:

- Type I—unsaturated air masses ($S^0 < 1$)
- Type IIa—supersaturated air masses ($S^0 \geq 1$) with T > 273.1 K
- Type IIb—supersaturated air masses with T < 273.1 K.

Unsaturated systems are relatively simple, and give rise to haze, with no cloud droplets. We will concentrate on Type II (supersaturated) systems and only on processes that occur within 8 hours.

In Type II systems, by the end of 10 seconds the initial phase of condensation of water vapor onto the CCN is essentially complete; the supersaturation is of order 10^{-4}; the water vapor concentration n_{vap} is very close to the saturation concentration, n_{sat}; and the liquid concentration n_{lq} (molec/cm^3) is very close to n_{sat} (S^0 - 1).

The processes of droplet coalescence, gravitational settling, and formation of ice crystals can be considered to begin from this point. The computations show that gravitational settling fluxes of liquid droplets are insignificant (less than about 3×10^{-7} g/cm^2•s) when the liquid water density is less than 2×10^{15} cm^{-3}, and the fluxes are roughly proportional to the 1.5-power of n_{lq} for larger values of n_{lq}. Thus the

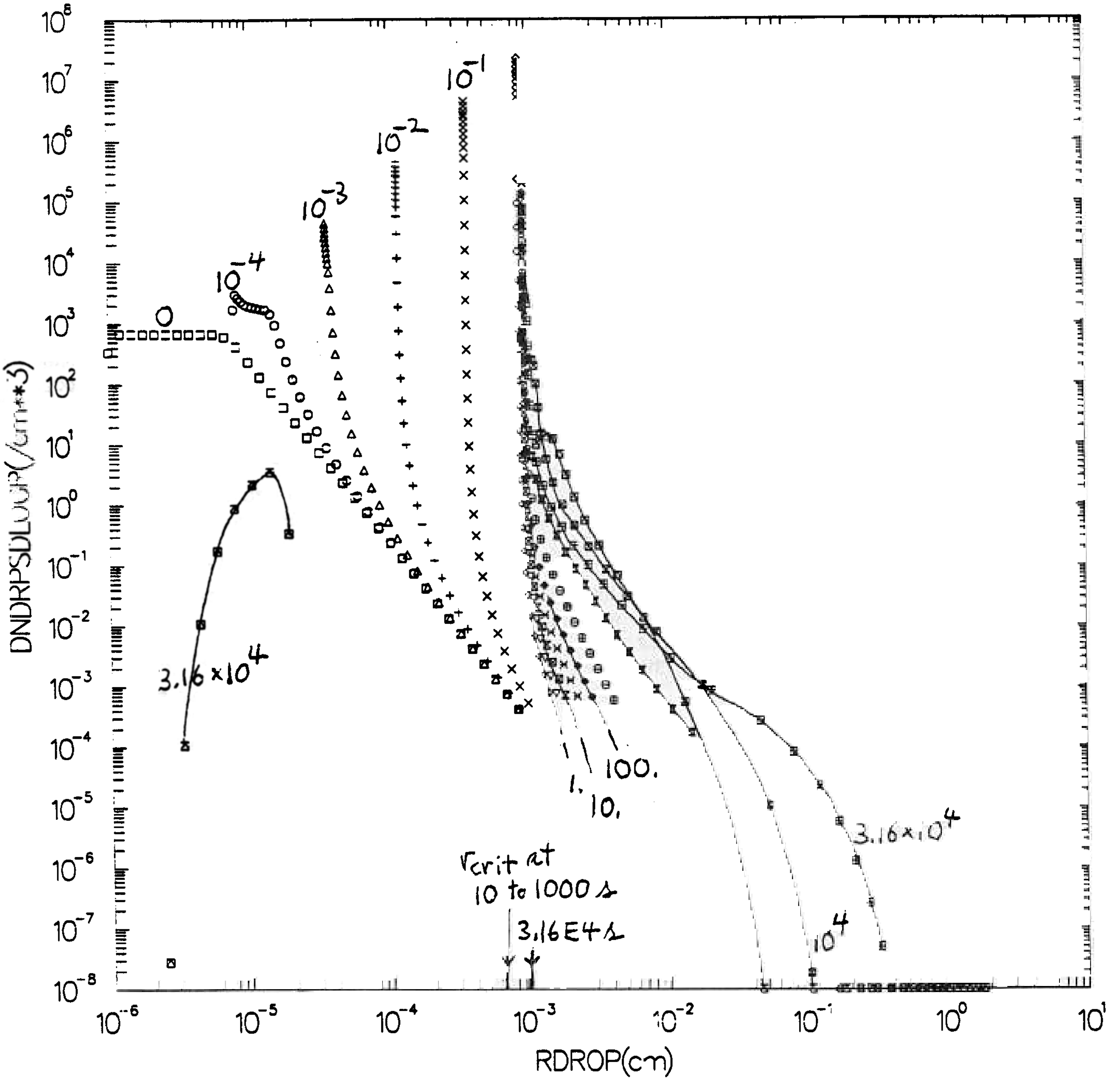

Figure 2a. Liquid drop number density vs log-radius distribution function *dN/d* log*r* (cm^3) vs log*r* for a cloud at 264 K with the "standard" number density distribution of ice condensation nuclei—for a sequence of times from zero to 3.162 x 10^4 s. The times are indicated on the curves. Also shown along the r axis are the Kohler critical droplet radii at selected times. The initial water vapor concentration in this case was 1.915 times the concentration of saturated vapor.

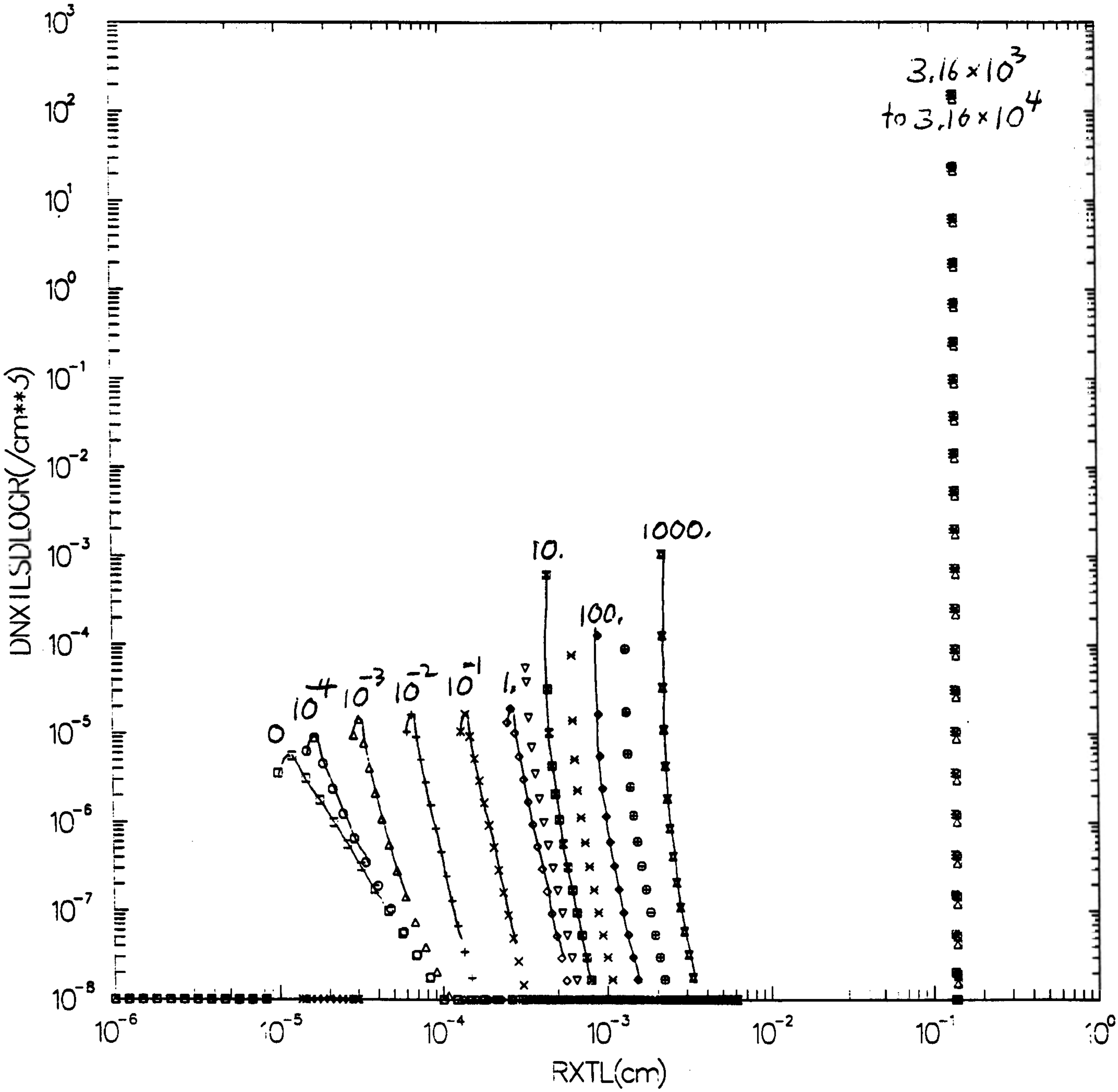

Figure 2b. Ice crystal number density vs log-radius distribution function $dN/d\log r$ (cm^3) vs $\log r$ for a cloud at 264 K with the "standard" number density distribution of ice condensation nuclei—for a sequence of times from zero to 3.162 x 10 s. The times are indicated on the curves. The initial water vapor concentration in this case was 1.915 times the concentration of saturated vapor.

water a cloud loses through falling droplets is insignificant if n_{sat} (S^0 - 1) < 2 x 10^{15}. n_{sat} can be computed from the Clausius-Clapeyron equation, so this sets a practical lower limit to the range of S^0 for clouds that can precipitate or change shape because of gravitational settling of droplets.

Ice crystals begin to have a significant effect on precipitation rates and/or total settling fluxes only at temperatures below about 266 K. For temperatures above 262 K the ice concentration n_{ice} (molec/cm^3) (for times less than 8 hours) is smaller than the n_{lq}, and the evolution of the ice distribution does not materially affect n_{lq} or the average droplet radius or the liquid drop settling flux. Nevertheless, the ice crystals continue to grow, both by condensation from the vapor and by collisions with liquid droplets, leading to ice crystal precipitation and settling rates (g/cm^2•s) that exceed those of the liquid water.

The results of computations that start from large values of S^0 exceeding about 1.2 show strong precipitation, which tends to dry out the cloud. In 8 hours such a cloud seems to evolve toward a fairly "typical" state in which the liquid water concentration, average drop size, relative humidity, and optical extinction coefficient are all fairly constant, depending only weakly on the temperature, the precise value of S^0, the ICN concentration, or the cloud vertical thickness. Typical 8-hour values of the liquid concentration, average drop radius, supersaturation, and extinction coefficient at temperature 273 K are 1.2 x 10^{15} molec/cm^3, 12 µm, 7 x 10^{-5}, and 2 x 10^{-5}, respectively.

Although the cloud vertical thickness has relatively little effect on the final concentrations of liquid water and vapor, it can have a pronounced effect on the total precipitation rate.

Reference

Pruppacher, H. R., and J. D. Klett. 1978. Microphysics of Clouds and Precipitation. D. Reidell Publishing Co., Dordrecht, Holland.