Precipitation Mechanisms in a Shallow Convective Cloud Model

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ABSTRACT

Precipitation mechanisms in shallow convective clouds are studied using an axisymmetric cloud model. Clouds are classified into continental and maritime clouds, and further subdivided into warm and cool clouds. Different microphysical factors were selected in the model to represent these different cloud systems. In maritime clouds condensation and collection processes are sufficient to develop precipitation, while in continental clouds graupel formation appears to be a necessary step. In the latter case recirculation of ice crystals is required to initiate riming so that it takes a longer time for rainfall initiation than in the maritime case. In maritime clouds inclusion of the ice phase does not change the rainfall pattern, although both raindrops and graupel contribute equally to precipitation.

The possibility of cloud modification is studied by increasing the ice nuclei concentration. In continental clouds an increase in ice nuclei concentration of 100 times more than the natural ice nuclei concentration causes activation of a higher number of ice nuclei at warmer temperatures, so that ice crystals can grow large enough to initiate riming during a single upward journey in the cloud without requiring recirculation. In this case it rains heavier and earlier than in the case of normal ice nuclei concentration.

1. Introduction

Precipitation mechanisms in clouds have been studied by many workers. Elucidation of the nature of such mechanisms is the central task of cloud physics.

After considering other processes, Bergeron (1935) suggested that ice crystal formation was a necessary initial stage in the development of precipitation. Later, Findeisen (1939) reached the same conclusion. Houghton (1950) compared the rate of mass increase by sublimation growth of ice crystals with that due to riming and concluded that graupel is the most likely particle involved in producing moderate precipitation. Langmuir (1948) proposed the drop-breakup process to explain heavy rain from deep clouds.

Meanwhile, pilots flying in the tropics and aware of Bergeron and Findeisen's assertion that the ice phase was a necessary condition for precipitation, hesitantly reported the observation of rain from warm clouds, where the cloud exists wholly below the freezing level. Bowen (1950) and Ludlam (1951) simulated the development of raindrops from warm clouds by assuming an initial existence of large drops.

Since that time, cloud physics investigators have studied the detailed microphysics associated with each type of possible precipitation mechanism. Precipitation mechanisms were discussed by Braham (1968) and Mason (1969) and Takahashi (1976b) succeeded recently in formulating the microphysics in an axisymmetric cloud model. The model has been used to study precipitation mechanisms in shallow convective clouds within different air masses. The possibility of precipitation modification was also investigated using the cloud model.

2. Shallow convective clouds within different air masses

Four types of clouds were considered. As shown in Table 1, warm and cool varieties of both maritime and continental clouds were studied. By fixing both the temperature and humidity profiles, different cloud types were characterized by selecting the proper microphysical factors.

The cloud nuclei concentration is taken as 50 cm^{-3} in maritime clouds and 500 cm^{-3} in continental clouds (Squires and Twomey, 1966). In "cool" clouds, the ice nuclei concentration is taken as 1 cm^{-3}. These nuclei have an activation probability as a function of temperature such that one nucleus per liter will be activated at a temperature of $-16°\mathrm{C}$ (Fletcher, 1962).

Environmental conditions are chosen arbitrarily to satisfy the condition that the cloud base is low, so that the calculation domain is as small as possible and the computer time is a minimum. The freezing level also is set near the cloud base so that the effect of the melting process on precipitation may be studied. The temperature at the ground is $+5°\mathrm{C}$, decreasing adiabatically to 1.2 km; the temperature lapse rate is 5°C km^{-1} to 2.0 km, and 3°C km^{-1} to 3 km. From 3 to 3.4 km, the temperature increases at a rate of 10°C km^{-1}, and then decreases by the same rate above 3.4 km.

The relative humidity at the ground is 85% and increases to 95% at 1.2 km; the humidity then decreases

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TABLE 1. Assigned ice (CI) and cloud (CN) nuclei concentrations in maritime and continental clouds under warm and cool air mass conditions.

	WARM	COOL
MARITIME	CI = 0 CN = 50	CI = 1 CN = 50
CONTINENTAL	CI = 0 CN = 500	CI = 1 CN = 500

CI : ICE NUCLEI l^{-1} T = - 16C
CN: CLOUD NUCLEI cm^{-3}

to 80% at 2 km and drops sharply to 20% at 2.4 km. This humidity value remains constant to the upper boundary. The calculation domain is 4 km vertically and 3.2 km radially. The grid size is 200 m in both directions.

The calculation scheme is that used by Takahashi (1976b). The input cloud droplet size distribution, assumed to be formed instantaneously on the cloud nuclei, is calculated in a one-dimensional model, including the nuclei size classification (Takahashi, 1976a). The input cloud droplet distributions shown in Fig. 1 were calculated at 200 m above the cloud base by assuming a total cloud nuclei concentration of 85 cm^{-3} (for maritime clouds) and 500 cm^{-3} (for continental clouds). In this paper the term *graupel* is used regardless of density.

3. Results

a. Precipitation mechanisms

1) MARITIME-WARM CLOUD

The cloud nuclei concentration is taken as 50 cm^{-3} and the ice nuclei concentration is set at zero. There is no freezing process.

Because of the low concentration of cloud droplets, each droplet can grow large enough to begin the collision process by the time the air moves from cloud base to cloud top. The modal drop size at 15 min and $H = 2.2$ km is 16 μm in radius.

The maximum updraft is 8 m s^{-1} and the cloud top height 2.4 km. In this paper a *cloud* is defined as the volume within which the liquid water content is greater than 0.01 g m^{-3}. The maximum liquid water content is 1.4 g m^{-3} near the cloud top at 15 min. The maximum drop concentration is 45 cm^{-3}. Rain is initiated at the cloud periphery (sides) because of the high updraft at the cloud center, and then propagates toward the cloud center.

At 30 min (Fig. 2), the maximum precipitation intensity is 9 mm h^{-1} at $H = 1$ km, $R = 0.6$ km. At the cloud center, precipitation particles are still carried upward by the updraft. The raindrop size, above which the concentration is 100 m^{-3}, is 800 μm in radius in the region of maximum precipitation.

2) MARITIME-COOL CLOUD

The cloud nuclei concentration remains 50 cm^{-3}, while ice nuclei are added and the freezing process included.

Airflow patterns are quite similar to those of the maritime-warm cloud. Because larger drops form near the cloud top (modal size, 16 μm in radius), nonrimed ice crystals ($r > 160$ μm in radius; concentration 0.1 m^{-3} at $H = 1$ km and 16 min) can capture these drops during a single upward journey and effectively form graupel. Graupel can grow further during fall from the cloud top to the cloud boundary (side). Precipitation intensity by graupel is 6 mm h^{-1}, while the precipitation intensity by raindrops is 8 mm h^{-1} (at 26 min, Fig. 3). Graupel melts beneath the freezing layer.

The size of the graupel, above which the concentration is 0.1 m^{-3}, is 2 mm in radius and the raindrop size, above which the concentration is 100 m^{-3}, is 800 μm in radius in the region of maximum precipitation intensity.

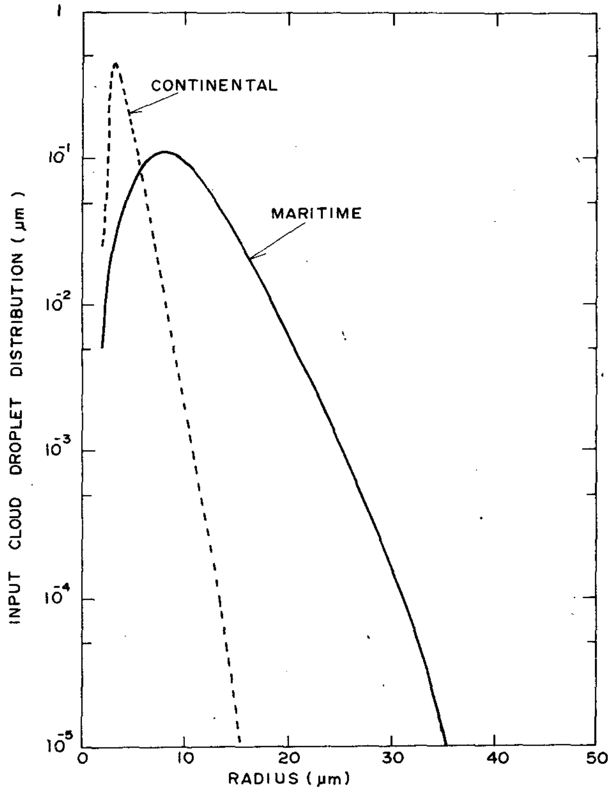

FIG. 1. Cloud droplet distributions calculated at 200 m above the cloud base in the cloud model (Takahashi, 1976a). It is assumed that cloud nuclei are activated and form these droplet distributions instantaneously. The dashed line is the distribution resulting from a cloud nuclei concentration of 500 cm^{-3} (continental case) while the solid line is the distribution when the cloud nuclei concentration is 85 cm^{-3} (maritime case).

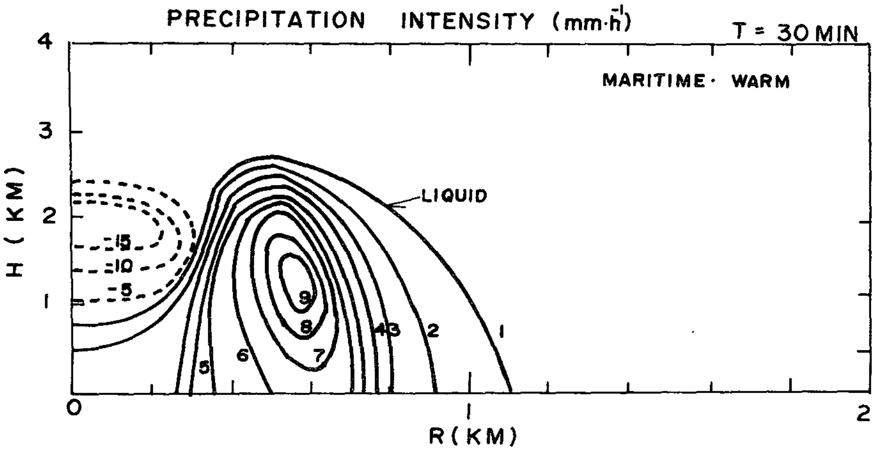

FIG. 2. Precipitation profile at 30 min in a maritime warm cloud. The dashed lines show the upward transport of liquid drops, while the solid lines represent precipitation.

At 26 min, the maximum graupel concentration (200 m^{-3}) appears near the cloud top, while the ice crystal concentration is 7 m^{-3} at the upper cloud boundary. The drop concentration is 38 cm^{-3} at the middle of the cloud and then decreases as drops are captured by ice crystals.

3) CONTINENTAL-WARM CLOUD

The cloud nuclei concentration is increased to 500 cm^{-3}. Ice nuclei were eliminated and there is no freezing process.

Because of the higher concentration of cloud droplets in the cloud, the growth rate of drops is slow. The modal size of cloud droplets is 6.5 μm in radius, with a narrow drop size distribution ($H=2.4$ km). Drops do not grow effectively by the collection process and the drop size, above which the concentration is 100 m^{-3}, is only 80 μm in radius at the upper cloud boundary (50 min). These drops are so small that they evaporate and no precipitation appears at the ground (Fig. 4).

The cloud maintains its shape for a long time. The maximum cloud droplet concentration is 430 cm^{-3} and the maximum liquid water content is 1.3 g m^{-3} near the cloud top at 50 min.

4) CONTINENTAL-COOL CLOUD

The cloud nuclei concentration remains at 500 cm^{-3}, while ice nuclei are added and freezing process included.

The maximum updraft is 7 m s^{-1} at $H=1.6$ km and at the cloud center (15 min), while a downdraft prevails over the whole area at 57 min. At 15 min, the modal size of cloud droplets is 6.5 μm in radius ($H=2.4$ km). These drops are too small to initiate drop growth by the collection process and too small to be captured by

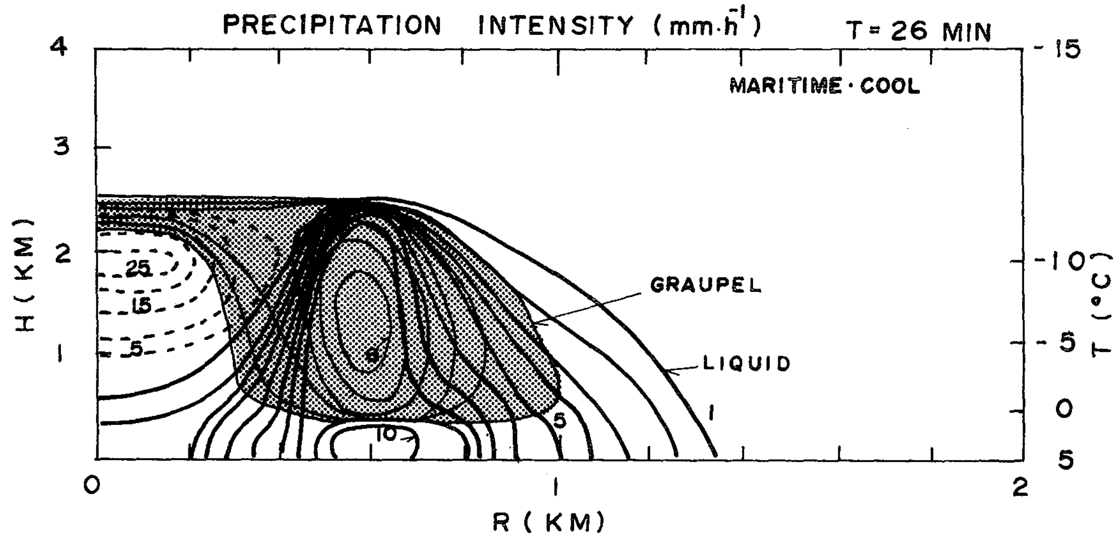

FIG. 3. Precipitation profile at 26 min in a maritime cool cloud. Thin solid lines show the precipitation due to graupel (shaded). Other notation as in Fig. 2.

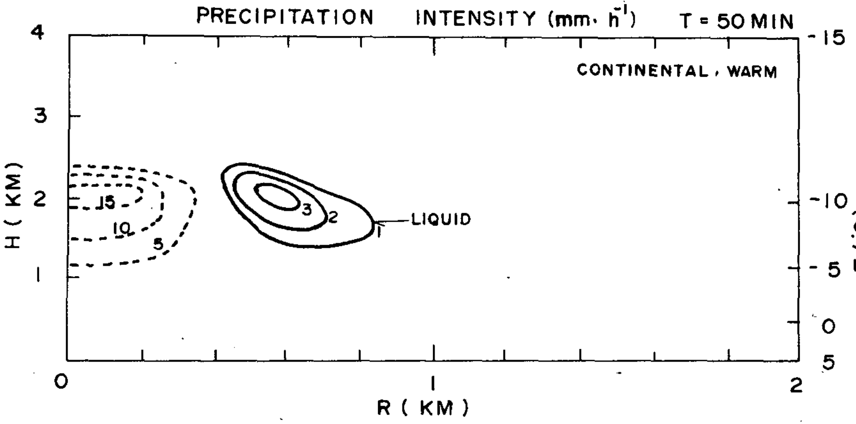

FIG. 4. Precipitation profile at 50 min in a continental-warm cloud. Notation as in Fig. 2.

ice crystals [the collection efficiency is zero when ice crystals are less than 100 μm in radius or when cloud droplets are less than 5 μm in radius (Pitter and Pruppacher, 1974)].

The non-rimed ice crystal ($r > 160$ μm in radius) concentration is only 0.05 m^{-3} at $H = 1$ km and 15 min. Because ice crystals recirculate from the cloud top to the cloud base along the outer cloud boundary, the ice crystal concentration increases by about two orders of magnitude at 30 min at $H = 1$ km. The number concentration of drops also increases slightly as the cloud develops due to the circulation of melted ice.

Recirculated ice crystals are large enough to capture cloud droplets and form graupel. Graupel of 2 mm in radius is formed at the cloud center in a concentration of 0.1 m^{-3} at 48 min, and produces precipitation intensity of 3 mm h^{-1} at the ground (Fig. 5). The graupel water content is 0.2 g m^{-3} near the cloud center. The maximum cloud droplet concentration is 400 cm^{-3} at the cloud center, while the ice crystal and graupel concentrations are 300 and 200 m^{-3}, respectively, near the cloud top. Graupel melts below the freezing level.

b. Cloud modification

In the continental-cool cloud, ice crystal recirculation is necessary to develop precipitation. As the number concentration of ice nuclei is increased, the concentration of ice crystals activated at warmer temperatures also is increased. Thus, large ice crystals may be formed and riming may begin during a single upward ascent without requiring ice crystal recirculation.

The ice nuclei concentration was then increased by 100 times throughout the continental cool cloud by fixing the activation probability.

The number concentration of ice crystals >250 μm in radius is 100 m^{-3} at 16 min and $H = 1.6$ km, which is two orders of magnitude higher than the value in the case without increasing the ice nuclei.

Without requiring the recirculation of ice crystals, the larger crystals will capture cloud droplets during a

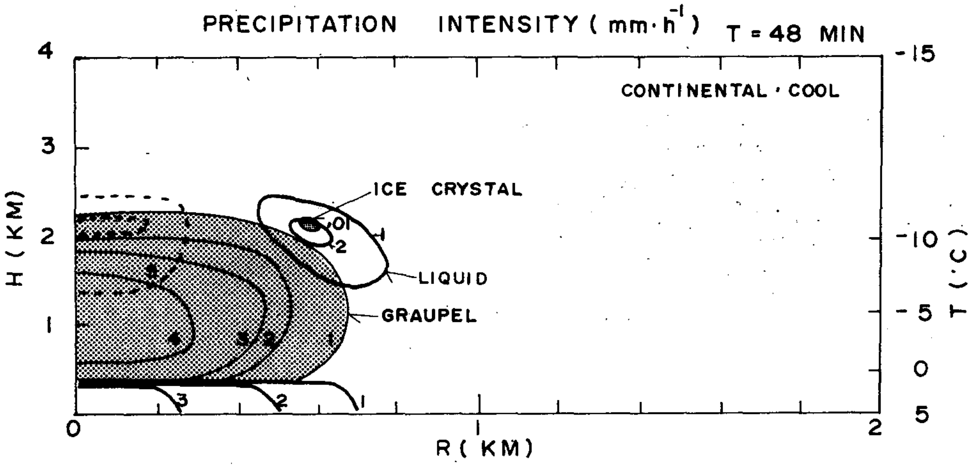

FIG. 5. Precipitation profile at 48 min in a continental-cool cloud. Thin lines show precipitation due to ice crystals. Other notation as in Fig. 3.

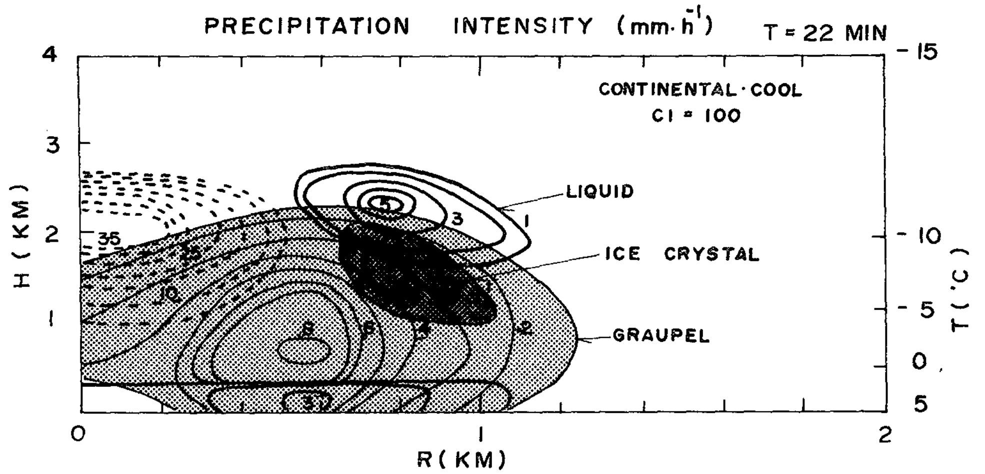

Fig. 6. Precipitation profile at 22 min in a continental-cool cloud where the ice nuclei concentration is 100 times higher than normal. Notation as in Fig. 5.

single upward journey and form graupel. At 22 min, the maximum precipitation intensity is 8 mm h^{-1} and part of the graupel melts below the freezing level (Fig. 6).

The maximum graupel and ice crystal concentrations appear near the cloud top; their magnitudes are 1 and 4 l^{-1}, respectively. The graupel size, above which total concentration is 0.1 m^{-3}, is 3 mm in radius.

The rainfall intensity from the cloud of increased ice nuclei concentration is much heavier and the rain begins earlier than in the case of the cloud with the original ice nuclei concentration (Fig. 7).

4. Discussion and conclusions

It was shown numerically that in shallow maritime clouds rain develops by condensation and collection processes within 30 min after initial cloud growth, while in a continental convective cloud graupel formation is a necessary prior step in developing rain (Table 2).

In the latter case, with normal ice nuclei concentration, ice crystal recirculation plays an essential role in the formation of graupel. Rain initiation, therefore, is delayed until 50 min. An increase of ice nuclei

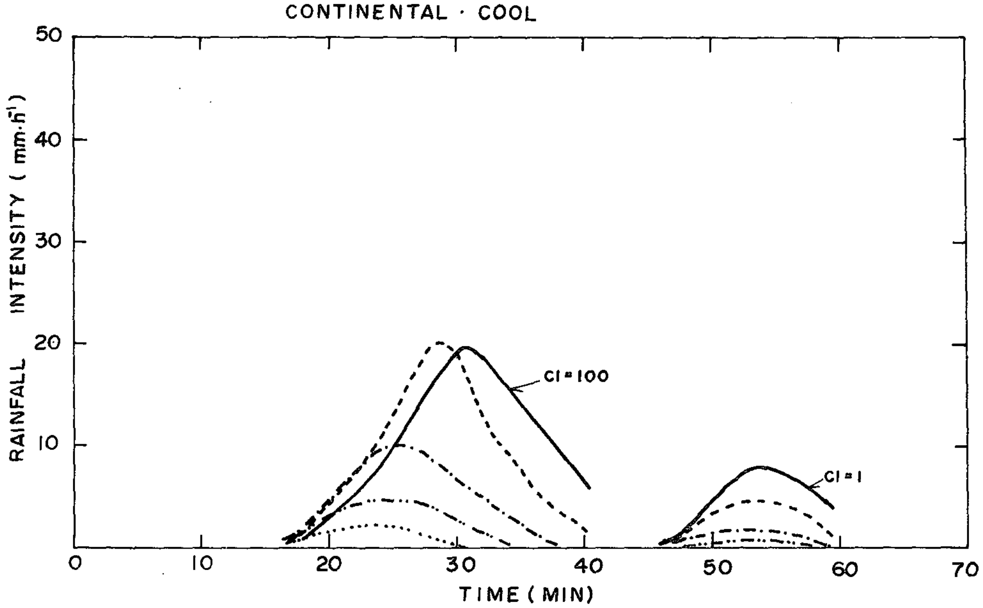

Fig. 7. Rainfall intensity at the ground. Lines labeled CI = 1 show the rainfall intensity in a continental-cool cloud with normal ice nuclei concentration. Lines labeled CI = 100 show the rainfall intensity when the ice nuclei concentration is 100 times higher than normal. The various lines show different radial locations by 200 m increments from the cloud center.

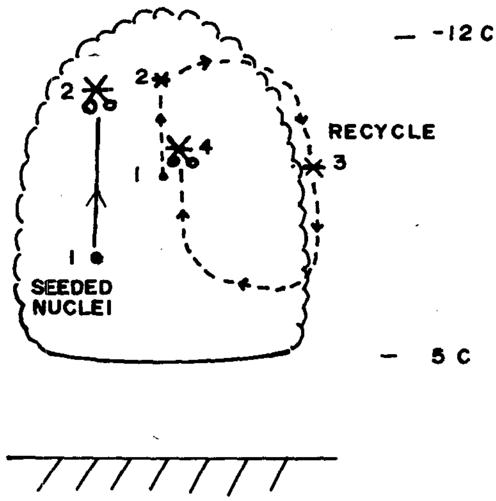

FIG. 8. Schematic of the proposed precipitation mechanism in continental-cool clouds. Ice crystal recirculation is required to form graupel in-cloud. When ice nuclei are seeded (shown on the left side of the cloud), ice crystals can commence riming during a single ascent without requiring recirculation.

TABLE 2. Model prediction of rainfall from maritime and continental shallow convective clouds in different air masses, along with the principal precipitation particle. Continental-cool clouds *may* be modified by increasing the ice nuclei concentration.

	WARM	COOL
MARITIME	RAIN (RAINDROP)	RAIN (RAINDROP - GRAUPEL)
CONTINENTAL	NO RAIN	RAIN (GRAUPEL)

↑
POSSIBILITY OF MODIFICATION

concentration by 100 times yields a high enough concentration of large ice crystals, grown in a single upward journey, to initiate riming in continental clouds and rain begins earlier through graupel formation (Fig. 8).

A deficiency of the present model is the assumption that ice crystals are of a plate form throughout the entire temperature range, even though column crystals are observed from -4 to -9°C (Ono, 1969). Therefore, the growth rate of ice crystal is overestimated in the present model.

Even with this overestimation, the present model clearly shows the necessity of recirculation of the ice crystals to develop graupel in the continental cloud. Most of the ice crystals which result from recirculation will be of plate form since those crystals are nucleated at the cloud top. The present conclusion, therefore, will not be changed significantly. In the case of the maritime-cool cloud, the contribution of graupel to precipitation will be reduced because of the formation of columnar crystals. However, it is important to note that the precipitation pattern is not changed radically in a maritime cloud, either with or without the ice phase.

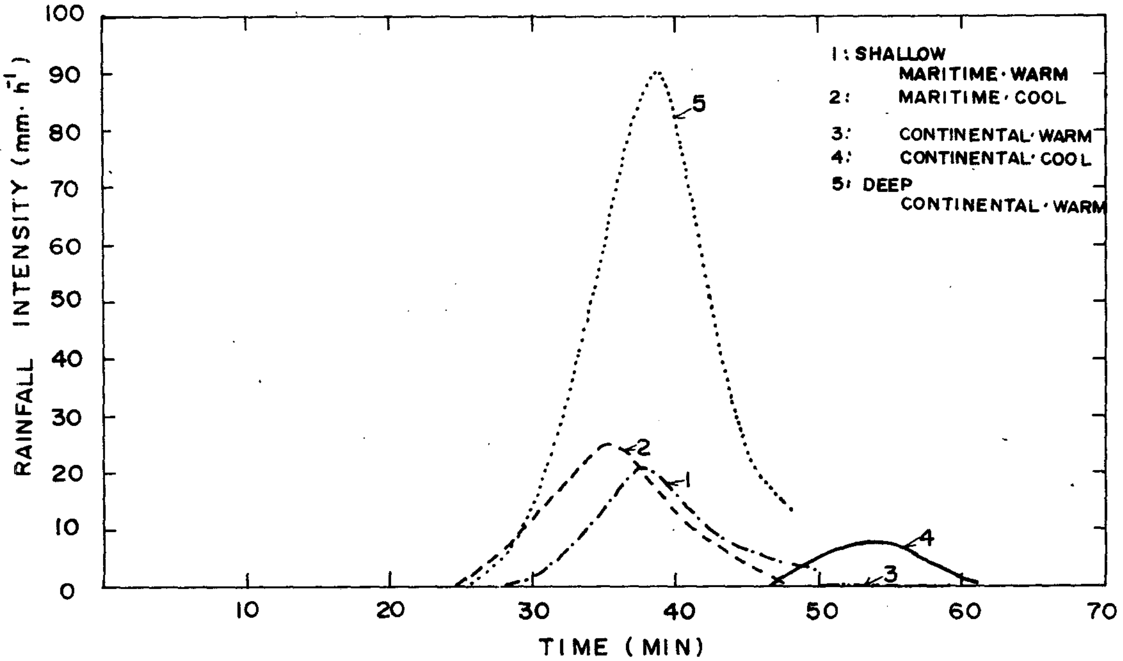

FIG. 9. Rainfall intensity at the cloud center and at the ground for the various cases discussed. The curve labeled 5 is for a deep continental-warm cloud case where the cloud thickness is about twice that of the shallow clouds discussed in this paper.

The assumed ice crystal shape will also affect the concentration of seeded ice nuclei for cloud modification, but the present model is satisfied in showing the possibility of cloud modification by increasing ice nuclei in the continental-cool cloud.

In one case, ice nuclei and the freezing process were eliminated in continental deep cloud (Takahashi, 1976b). Since the cloud (cloud depth, 4 km) can grow tall enough to produce larger cloud droplets by condensation, and so initiate the collection process in the upper part of the cloud, rain is produced without the ice phase (Fig. 9).

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