A "FROZEN DROP" PRECIPITATION MECHANISM OVER AN OPEN OCEAN AND ITS EFFECT ON RAIN, CLOUD PATTERN, AND HEATING

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1. INTRODUCTION

Videosonde data from the East Asian monsoon area shows very low concentrations of ice crystals in clouds over the open ocean. These results contrast strongly with the many crystals measured over the maritime continent (Takahashi, 2006). Different precipitation mechanisms are held in each region: "Frozen Drop" process over the open ocean and the "Mixed" rain process over the maritime continent. These differences may affect not only the rainfall but also cloud organization and vertical latent heat profiles as well. The latter are sensitive to the Walker circulation and 30 to 60 day oscillations (Hartman et al. 1984, Lau and Peng, 1987).

This paper reports examination of the modification of rainfall, cloud organization, vertical latent heat profiles in the tropics, using different precipitation processes. The three-dimensional, microphysical cloud model reported by Takahashi and Shimura in 2004 has been used. The reason for such a difference in ice crystal concentrations between an open ocean and a maritime continent was also examined by the analysis of cloud drop images observed by videosondes.

2. MODEL

The model is non-hydrostatic, anelastic, and uses detailed microphysics. Precipitation particles are classified by mass using bins: 33 for water drops, 21x5 for ice crystals, 45 for graupel and 45 for hail and frozen drops. As is shown in Fig. 1, the microphysical processes include cloud nucleation, condensation, collection, breakup, ice nucleation, deposition, riming, freezing, and accretion.

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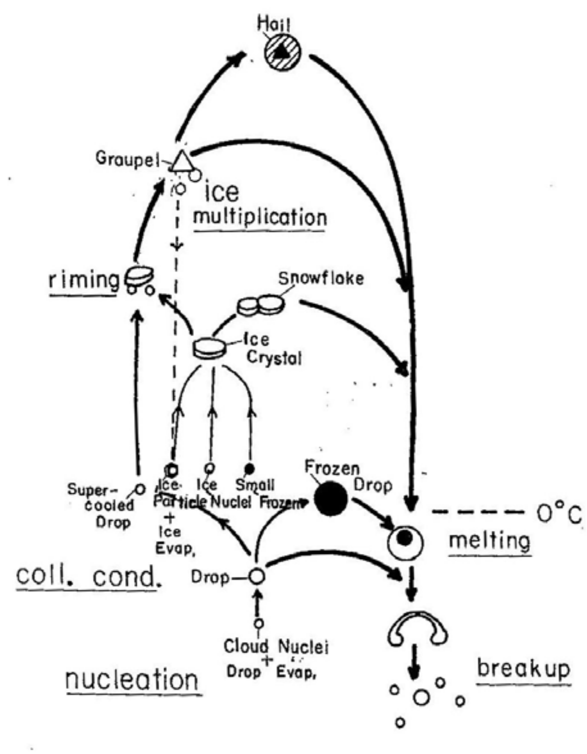

Fig. 1 Model microphysical processes

The number of cloud nuclei potentially able to grow cloud droplets in typical maritime air is set at 300 cm^{-3}. In the "Mixed" process the number of ice nuclei potentially able to be nucleated is set to 1/cc. In the "Frozen" process there is no ice nuclei. Here, drop freezing is enhanced by forcing all drops > 400 μm radii to freeze below -5°C. Ice is eliminated from rain production in the "Warm" process.

An initial, random impulse is given at 0.3 km. Every five minutes a number between -0.5 and 0.5 is drawn every 5 minutes. After being divided by total time steps within 5 minutes, the random impulse is given at each time for 30 minutes to

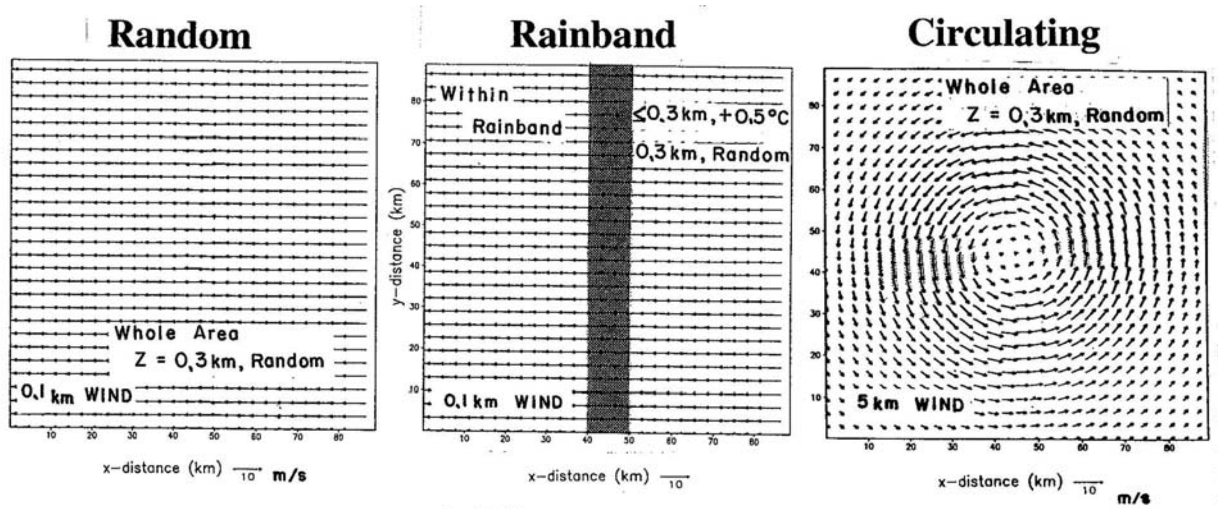

Fig.2 Initial setups for Random, Rainband, and Circulation

the potential temperature (Fig. 2). In order to simulate a rainband, the temperature in the area in the center of the cloud, 10 km wide and below 0.3 km, is increased by 0.5°C followed by a random impulse at 0.3 km for 30 minutes in the same area. Two different wind profiles have been used, the first being low-level with linear shear. Here the wind at the lower boundary is at -9.0 m/s, increasing linearly to 3.0 m/s at 2 km and retaining the same velocity to 3.5 km where it turns northeasterly. The other is circulating, as in Kurihara (1975). Active cloud developments have been observed over the central area of Indo-China peninsula in association with mid-level vortex (Takahashi, 2006). Here, below 5 km, the winds are the same then decrease linearly to 10 km. The temperature and humidity profiles are as in typical tropical soundings and the CAPE is 2300 J/kg.

Cyclic conditions are used to the sides and upper and lower boundaries are rigid with free slip conditions. For the x and y axes, the grid intervals for x and y are 400 m and for z, 200 m. The calculation domain is 227x227x61. Message-parallelism with eight nodes was used. To handle the large amount of data and reduce computer time, a parallelization technique with two-dimensional horizontal (x-y) domain decomposition was used. All the processors were controlled and communicated through a Message-Passing Interface Library.

3. RESULTS-CLOUD MODEL

a. Rainfall

For the Random case, rainfall was highest with “Mixed” process and lowest with “Warm” (Fig.3). After 150 minutes, the “Frozen” process reduced 20% the rainfall accumulated with “Mixed” and the “Warm” by 70%. The same tendencies were observed with the Rainband and Circulation cases. The conversion rate from water vapor to raindrops was 1% with the “Warm” process, increasing to 4% when the ice process activated. It was rather surprising to find a conversion rate in the Rainband as high as 5% with “Frozen” process, higher than the “Mixed” process at the later time. In the Circulation case the conversion rate increased to 6% for both “Mixed” and “Frozen” processes.

b. Cloud Organization

After the initial 40 to 60 minutes, the cloud cells in the Random case lined up along the low level winds. With the “Mixed” process the cells merged with some growing cells. At 120 and 130 minutes, a cluster of several rain cells near the center suddenly broke up. At the center of the cluster, a rotating cell, 15 km wide, developed. This cell persisted longer, its downdraft helping to push the other cells away from the center to where they developed into a ring (Fig.4). With the “Frozen” process, however, the rain cells increased in size to 10 to 20 km. Cells in the “Warm” process were as small as a few km. No clear central organization was detected in either of these cases

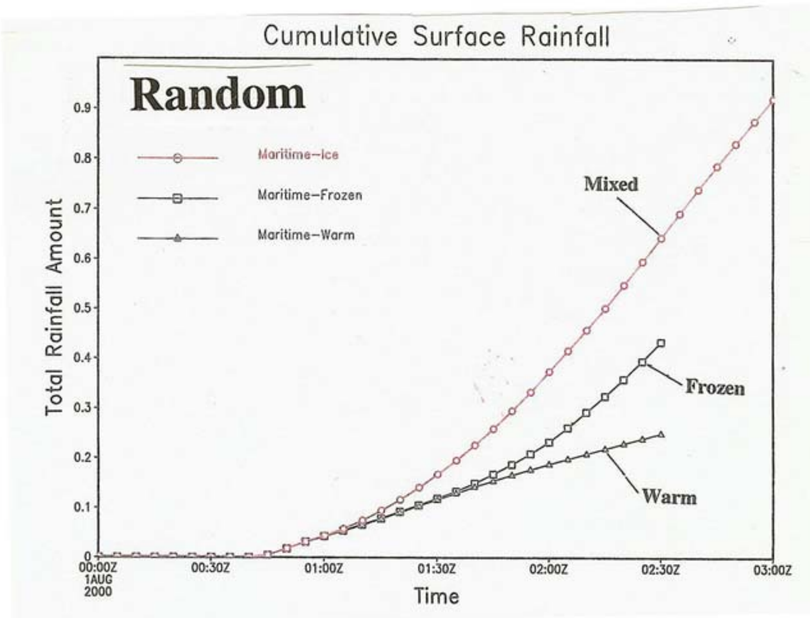

Fig.3 Cumulative surface rainfall for Random case with different precipitation mechanisms.

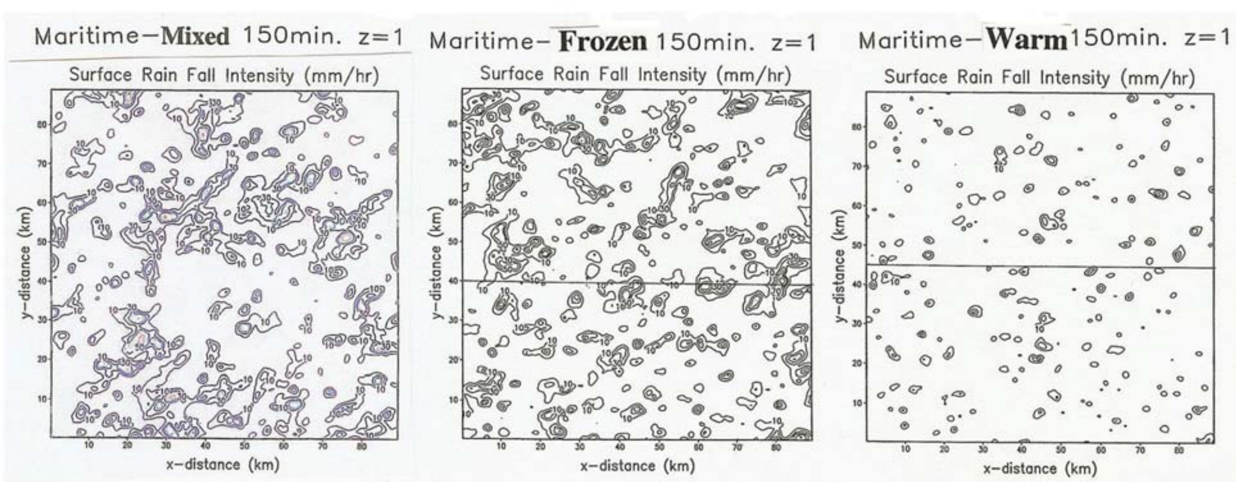

Fig.4 Surface rainfall intensities > 10 mm/h at 150 min, for the Random case with “Mixed, Frozen and Warm” processes.

In the rainband case, as the cloud developed, the outflow from the rain-induced downdraft enhanced cells forward of the cloud band. The rainband increased in width as these cells were absorbed into the main cloud. In this case, with the “Mixed” process, as the ice process activated, at 110 min, a tilted updraft formed there and main rainfall area shifted to the front as it diminished at the rear (Fig.5, 120 min). With the “Frozen” process, however, heavy rain continued at the cloud trailing edge because of the weaker latent heat release from fewer ice crystals. The forward cell did not develop. With the “Warm” process, isolated cells developed sporadically toward of the narrow rainband, moving west by transferring the primary rainfall to new cells.

In the Circulation case, with the “Mixed” and “Frozen” processes, cloud cells merged, forming spiral cloud bands (Fig.6). Downdrafts from two adjacent cells enhanced the updraft of a cell between them and, at the upper levels,

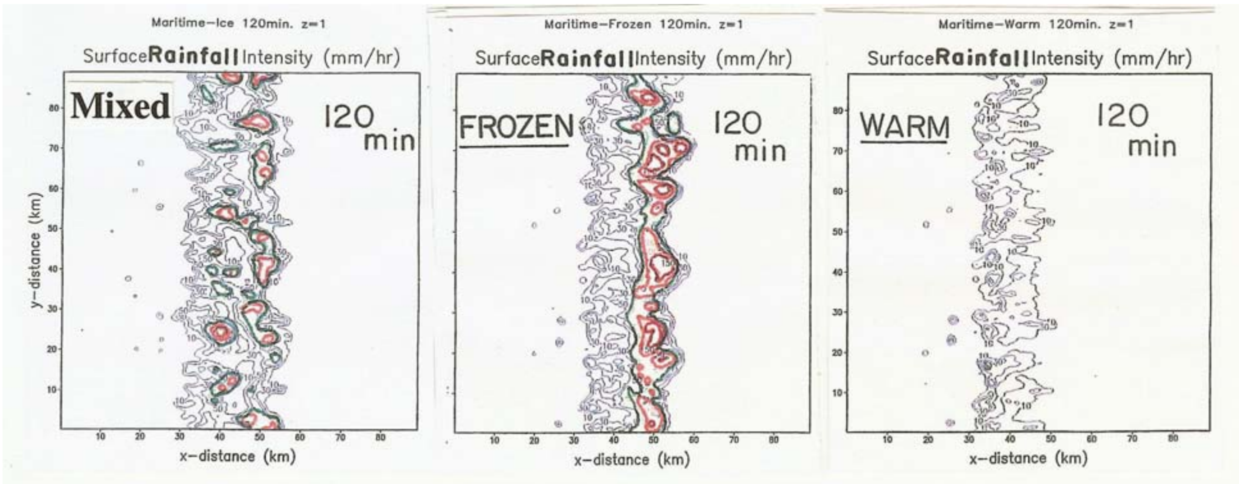

Fig.5. Same as Fig.4 except Rainband at 120 min.

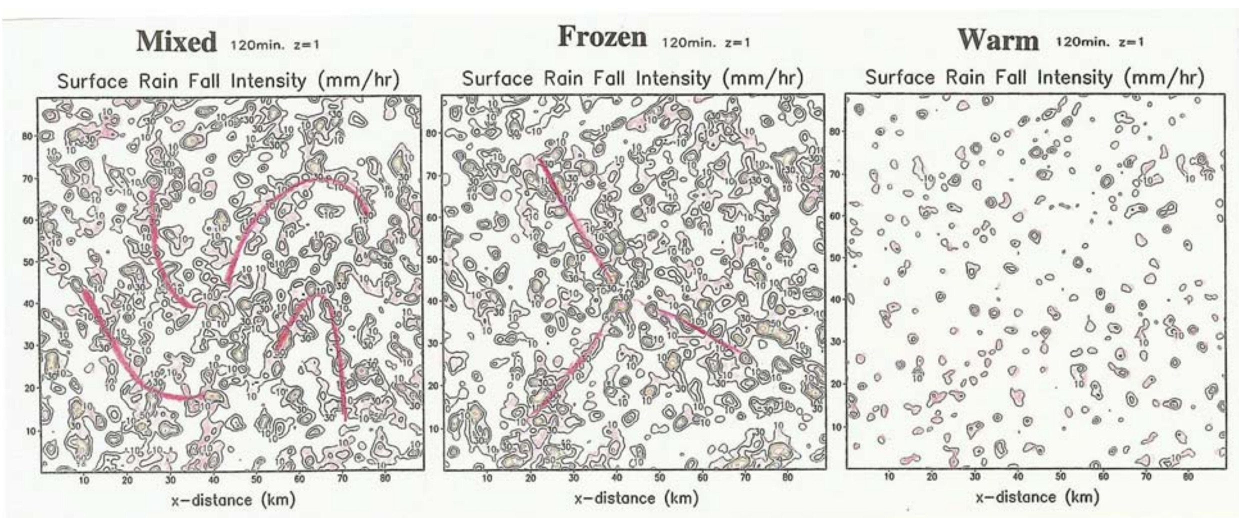

Fig. 6. Same as Fig. 4 except Circulation at 120 min.

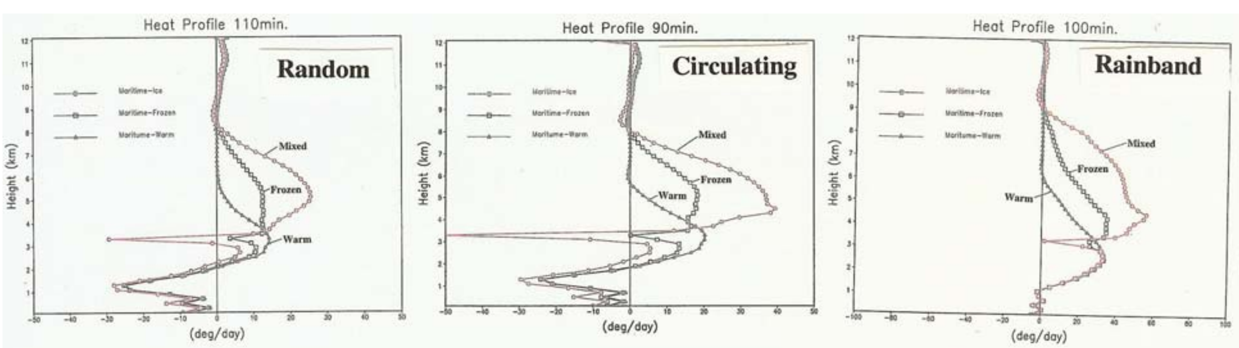

Fig. 7. Latent heating profiles at 110 min for Random, 90 min for Circulation and 100 min for Rainband, with different precipitation processes.

a high updraft dragged air from a neighboring cell. The cloud cells in this way combined, forming a large, tilted cell, the development proceeding more slowly with the "Frozen" process.

c. Vertical latent heat

The heating rate has been calculated as in Yanai et al. (1973) and, since radiation heating is typically lower than cloud latent heat, it has not been considered. The two peaks calculated are shown in Fig. 7. They are at lower levels with drop condensation growth and at higher ones through ice crystal deposition. The "Warm" process, therefore, did not form the upper peak. Initially, the heating in the "Frozen" process was similar to that in the "Warm". In the Random and Circulation cases, through drop evaporation, the sink in the heating rate occurred at a lower level.

4. VIDEOSONDE RESULTS

Data from a cloud drop imaging sensor on a videosonde launched into mostly developing tropical clouds showed quite active ice crystal formation on frozen cloud drops (Fig.8). On 1 August 1997, a depression enhanced westerlies over the East China Sea and isolated clouds developed over Chaing Rai (C1). The videosonde data from this date shows a narrow concentration of cloud drops, peaking at 25 µm diameter at -4°C. At -5°C, the data indicated a concentration of columnar crystals, 0.4/cc, and, at about -15°C, a large concentration of frozen drops, 0.6/cc. There was no appreciable graupel formation by flush system of videosonde.

Over Ubon, on 7 August 1998 (U1), when the 500 mb Circulation combined with a low level trough, an intense convective cloud developed with an 8 m/s updraft. The drop distribution at the freezing level was also narrow and the freezing process slow. At warmer temperatures there were few columnar crystals, but, above -7°C, large frozen drops appeared and, above -30°C, ice crystals increased in number and there was active graupel formation.

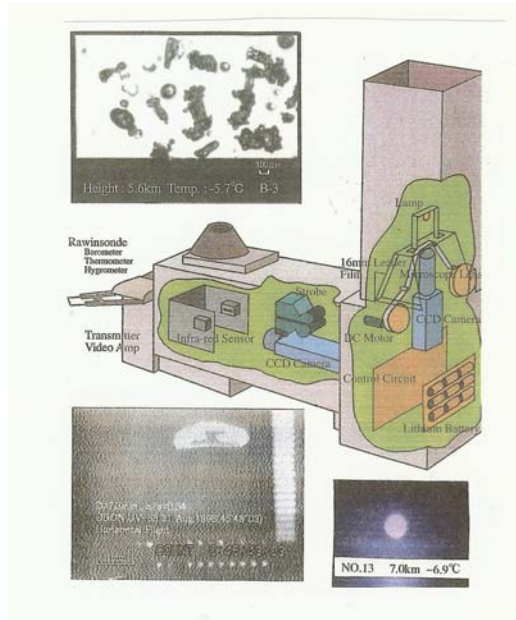

Fig. 8. Videosonde

Over the mountainous terrain of the northern coast of Brunei, on 3 December 1996 (B9), a low-level vortex produced active convective clouds. Videosonde data showed rather broad distribution of cloud drops at 2°C. At -6°C there were many columnar crystals, some heavily rimed. Even at -11°C there were many such crystals mixed with some frozen drops and plates. The pristine ice crystal concentration was 0.4/cc at -5°C and 0.6 at -13°C. There was active graupel formation, even at the warmer temperatures. At -45°C, the pristine ice crystal concentration increased significantly to 2/cc, seemingly to be newly formed frozen drops activated by a local updraft.

When upper Circulation was active at mid-level over Ubon on 10 August 1998 (U5), drop growth rate was very high. Cloud drop distribution at 4°C showed double peaks with few small drops. Because the frozen drops were large, there was no formation of columnar crystals.

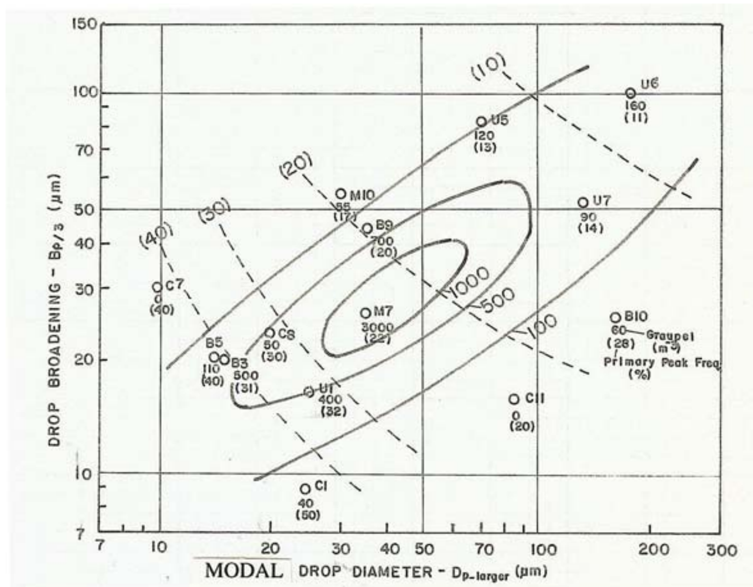

Fig. 9 Peak number concentration of graupel with respect to modal cloud drop diameter and drop broadening near the freezing level

The large frozen drops, some of them heavily rimed, increased in number above -15°C and, at -36 and -54°C the pristine ice crystal numbers also increased by the formation of new frozen drops.

These observations suggest that in tropical clouds, active ice crystal formation occurs through cloud drop freezing. Columnar crystals grow first on moderately-sized frozen drops and, with abundant cloud drops then grow graupel. Conversely, graupel growth on large frozen drops is slow, however, once grown at low temperatures they generate new pristine ice crystals.

Freezing activity is highly dependent upon drop size and updraft. When the modal drop size is larger than 70 µm diameter, all drops freeze by -7°C. When the modal drop size is 20 µm, however, and with updrafts as high as 8 m/s, some drops remain liquid to -30°C. When the modal drop size is very large, drops freeze at warmer temperatures. The growth of columnar crystals is retarded because of large frozen drop size. The absence of small drops will slow graupel formation. On the other hand, if the modal size is very small, drop freezing will be slow and graupel growth will also be retarded. Ideally, high graupel growth and ice crystal formation requires a modal size of 30 to 50 µm, broadening around 30 µm (Fig.9).

5. Summary

The different number concentrations of graupel and ice crystals over the ocean and over the maritime continent will lead to different precipitation mechanisms. Cloud model demonstrated that with different precipitation mechanisms, rain, cloud patterns, and vertical heating profiles are highly variable. The primary results of these investigations are as follows.

a. Through efficient conversion from water vapor to hydrometeor through ice phase growth, “Mixed” process produced the highest rainfall.

b. With the “Mixed” process the cloud organization developed well. With the “Frozen” process the rainfall remained in a line at the rear of the cloud.

c. In the Random and Circulation cases negative latent heat, produced by drop evaporation from small clouds, persisted in the lower levels

Observation showed that freezing process is highly active in East Asian monsoon clouds. Growth of pristine columnar crystals is the key for the graupel and ice crystal formation. Cloud drop size distribution near the freezing level therefore, plays a critical role. This finding is different from Hallett-Mossop process in which graupel is prerequisite for efficient ice production. Low concentrations of ice crystals and graupel over the open ocean was attributed to expected large drop formation due to low CCN in this area.

6. References

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