Different Precipitation Mechanisms Produce Heavy Rain with and without Lightning in Japan Baiu Storm

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ABSTRACT: The Baiu front brings frequent bouts of heavy rain to Japan in two types of cloud systems, one with high lightning activity and the other with low lightning frequency. To find the basis for this difference, data from Baiu and non-Baiu Japanese heavy rain events were compared with videosonde data from various cloud systems across East and Southeast Asia. This analysis suggests that Baiu heavy rain is produced by two different precipitation mechanisms: by graupel growth in high-electrical-activity clouds and by frozen drop growth in low-electrical-activity clouds. High electrification is achieved only in graupel-growing clouds, where numerous ice crystals also grow and the riming electrification process is active.

INTRODUCTION

It is well established that there are two basic types of torrential rainfall: one with frequent lightning (Soula et al. 1998, and others) and the other with little or no lightning (Lang et al.2004, and others).

In 2008 and 2009, five heavy rain events occurred in Japan (Fig. 1 and Table 1). They are Hofu, Sasaguri, Dazaifu, Sayo and Zōshigaya heavy rains. Lightning activities at Hofu and Zōshigaya were high while low at Sasaguri, Dazaifu and Sayo

Globally, rainfall amount per CG-lightning varies greatly by geographical location (Petersen and Rutledge, 1998), including a sharp difference between land and ocean, with lightning frequency almost an order of magnitude lower over the ocean (Christian et al. 2003, and others). In addition, between the 0 and -20°C levels, radar echo intensity decreases steeply with height (6 dBZ/km) in tropical thunderclouds but decreases slowly with height (1.5 dBZ/km) in continental thunderclouds (Zipser and Lutz 1994, and others). Williams et al. (1992) and Rutledge et al. (1992) proposed that the difference in lightning activity between the land and ocean is caused by the difference in updraft strength between these locations. This concept is hypothesized also to explain the large difference in lightning activities between storms in the same location.

However, updraft weak enough to explain the absence of lightning would not be expected to support robust graupel growth, and it has been difficult to explain how the resulting, graupel, relatively small in number and size, could support the heavy rainfall observed.

Riming electrification (Takahashi 1978, and others) has been found to be the main charge separation mechanism. This is also conclusion reached for recent Hokuriku winter snow clouds after analysis of 20 videosonde flights in 2012, all equipped with the HYVIS device for observing cloud droplets.

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The present work examines the wide range of electrical activity in heavy-rain-producing Japanese clouds, from very high to nearly absent, in an effort to explain the mechanistic basis of this difference.

2008-2009 HEAVY RAIN EVENTS IN JAPAN

On July 20, 2009, the Baiu front, which stretched from the southern end of the Korean Peninsula to Japan, moved slowly to the south (Fig. 2a). At Hofu City, Yamaguchi Prefecture, the winds at 700 mb were from the west, and heavy rain struck as cloud cells from the west merged with cloud clusters that had developed in place along the Baiu front. The inundation of Hofu peaked on July 21, 2009: daily rainfall was 275 mm, and peak hourly rainfall was 63.5 mm. On July 21, Hofu was struck by three heavy rain events between 05:00 and 13:00 local time (JST) (Fig. 2b). Total lightning activity within the 100x100 km^2 area centered on Hofu from 3:00 to 14:00 on July 21 was 14,307 flashes (1301 flashes/hour). Cloud-to-ground lightning (CG) dominated. Note that lightning activity was very high during Stage 1 (05:00-07:30), lower during Stage 2 (07:30-09:30), and still lower during Stage 3 (09:30-12:30). Within this same 100x100 km^2 area, radar echo intensity vs. altitude was also tracked. During Stage 1, the 45 dBZ echo altitude reached its highest point of the day, and echo intensity decreased slowly with height. The 45 dBZ echo altitude was lower during Stage 2; and it was even lower during Stage 3, remaining near the melting level.

On July 24, 2009, the Baiu front held stationary, centered over Tsushima Island (Fig. 3a). In Fukuoka Prefecture, Kyushu, winds at 700 mb were from the southwest, and heavy rain struck when rain cells from the southwest merged with the main cloud cluster. At Sasaguri, a town just to the northeast of Fukuoka City, daily rainfall was 251 mm and peak hourly rainfall was 100 mm h^{-1} (Fig. 3b). Lightning activity, however, was relatively low, with only 1015 flashes from 15:30 to 24:00 (119 flashes /h) within 100x100 km^2 area centered on Sasaguri. Cloud-to-Ground (CG) lightning dominated. Over the period of highest rainfall intensity (~18:30 – 19:30), the 45 dBZ radar echo altitude stayed near the melting level, and radar echo intensity decreased sharply with height.

Since Dazaifu heavy rain is similar to Sasaguri in character, Sasaguri heavy rain was taken to be representative of both. Sayo heavy rain showed the similar character to Sasaguri while Zōshigaya heavy rain showed the similar profile to Hofu.

PRECIPITATION MECHANISMS OF RAIN SYSTEMS IN EAST AND SOUTHEAST AREA

Precipitation particle distributions differ greatly by geographical location. To investigate how these differences affect electrical activity, we analyzed data from our database of >200 videosonde flights across East and Southeast Asia (Takahashi, 2006).

A sample of data acquired by videosonde is displayed in Fig. 4. Videosonde (K1) was launched into moderate rain during the Baiu season at Kagoshima and recorded a precipitation particle distribution typical of Baiu clouds of the mixed regime (see below). Frozen drops grew in a narrow layer above the melting level, while graupel grew over a much deeper volume extending from the melting level to the cloud top.

From our database, we examined videosonde data from all of the heavy-rain-producing clouds, defined as videosonde flights in which rain mass content was ≥ 500 mg m^{-3} (Fig. 5a). These precipitation processes could be divided into three, separate, regimes based on their relative abundance of graupel vs. frozen drops (Takahashi, 2006): (1) In inland China and the

Indochinese Peninsula, graupel content was high and frozen drop content was low (graupel regime); (2) Over small Pacific islands such as Ponape and Manus, frozen drop content was high and graupel content was low (frozen-drop regime); and (3) In boundary areas where large land masses border the ocean, both graupel and frozen drops were numerous (mixed regime). In these clouds, the sum of graupel and frozen-drop concentrations multiplied by ice crystal concentration, i.e. ([graupel] + [frozen drop]) x [ice crystal], correlated strongly with graupel mass content but did not correlate with frozen drop content (Fig. 5b), suggesting that ice crystal production is associated with graupel production but not with frozen drop production. In comparing data from the videosonde flights launched at Tanegashima and Melville, cloud space charge increased with increasing graupel content but not with frozen drop content (Fig. 5c).

COMPARISON OF JAPANESE HEAVY RAIN EVENTS WITH EAST AND SOUTHEAST HEAVY RAIN

We next sought to compare the heavy-rain-producing, East and Southeast Asian clouds (videosonde data) with the clouds of the four Japanese heavy rain events (radar data) (Fig. 6). In order to do this, the videosonde-acquired, precipitation-particle measurements were converted to radar echo intensities by assuming that the particles follow the Marshall-Palmer size distribution.

Four flights detected dominant frozen drops, and 11 detected graupel or mixed graupel-frozen drop. For each flight, the height and density of the particle column were described by plotting the highest altitude reached by each radar echo intensity. On average, in the graupel-mixed groups, compared to the frozen drop group, radar echo intensity decreased with height less steeply and radar echo extended to substantially higher altitudes (Fig. 6-right panel).

Next, the Japanese heavy-rain-event radar data were similarly analyzed by plotting the highest altitude reached by each radar echo intensity (within the indicated time range) (Fig. 6- left panel). The plotted events are Hofu (0500-0730), Sasaguri (1800-2000), Sayo (1830-2200), and Zōshigaya (1030-1330). In the high-lightning-activity, heavy-rain events (Hofu Stage 1 and Zōshigaya), compared to the low-lighting-activity, heavy-rain events (Sasaguri and Sayo), radar echo intensity decreased with height somewhat less steeply and radar echo extended to substantially higher altitudes.

When the Japanese heavy-rain-event radar data are compared to the videosonde-derived radar data, a striking similarity is apparent (Figure 6).

In both, cloud radar echo intensity profiles fall into two types, one of which is ‘taller’ (echo intensity decreases with height less steeply and extends to higher altitudes). Among the videosonde-observed clouds, the tall-echo clouds are the graupel clouds, while the short-echo clouds are the frozen drop clouds. Among the Japanese heavy-rain-event clouds, the tall-echo clouds are the high-lighting-activity clouds, while the short-echo clouds are the low-lightning-activity clouds. This suggests (1) that in the Japanese heavy-rain-event clouds, the high-lightning-activity clouds are graupel-dominant, while the low-lightning-activity clouds are frozen-drop dominant, and (2) that the difference in electrical activity results from the difference in the relative content of graupel and ice crystals. The main reason for the weakness of electrical activity in frozen-drop-dominant clouds is probably that the concentration of ice crystals is too low to support much riming electrification.

CONCLUSION

Here, we propose that the critical difference that causes this divergence in electrical activity in storm systems not in updraft strength, but rather, in precipitation mechanism. The graupel precipitation mechanism is associated with frequent lightning, while the frozen drop precipitation mechanism is associated with less lightning (Fig. 7). Ice crystal concentration increases with graupel concentration but not with frozen drop concentration, and it is the interaction between graupel and ice crystals that charges the cloud (riming electrification).

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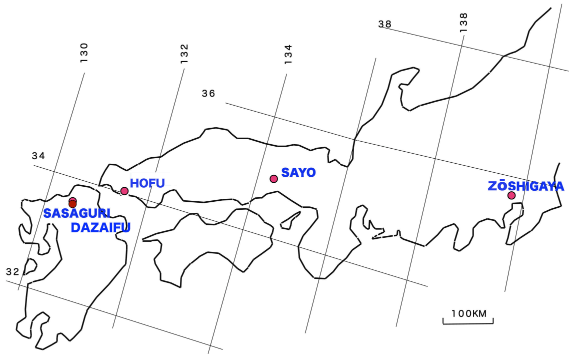

Fig. 1. Major heavy rain events in Japan in 2008 and 2009

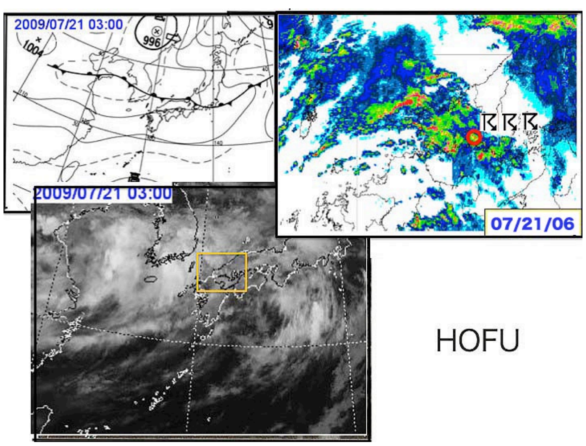

Fig. 2a. Hofu heavy rain event. Upper-Left: Surface weather map. Lower-Left: Satellite image. Upper-Right: Surface radar echo intensity profile with Hofu City marked by a red circle. The area shown corresponds to the yellow box in the low-left Satellite image.

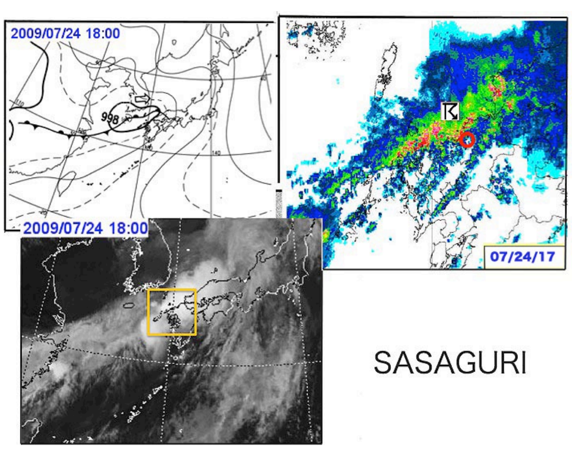

Fig. 3a. Same as Fig. 2a except Sasaguri heavy rain event.

City	Observation Date	Daily Rainfall (CAPE)	Lightning Count, Time (Flash Freq.)	Ratio of Cloud-to-Cloud Discharge
HOFU (34.0°N, 131.5°E)	21 JULY 2009	275 mm (986 J/kg)	14,307 flashes, 03:00-14:00 (1301 flashes/h)	6 %
SASAGURI (33.6°N, 130.5°E)	24 JULY 2009	251 mm (119 J/kg)	1015 flashes, 15:30-24:00 (119 flashes/h)	19 %
SAYO (35.0°N, 134.3°E)	9 AUG. 2009	326 mm (138 J/kg)	121 flashes, 00:00-24:00 (5 flashes/h)	95 %
ZŌSHIGAYA (35.7°N, 139.7°E)	5 AUG. 2008	134 mm (587 J/kg)	6212 flashes, 09:00-18:00 (690 flashes/h)	81 %

Table 1. 2008-2009 heavy rain events.

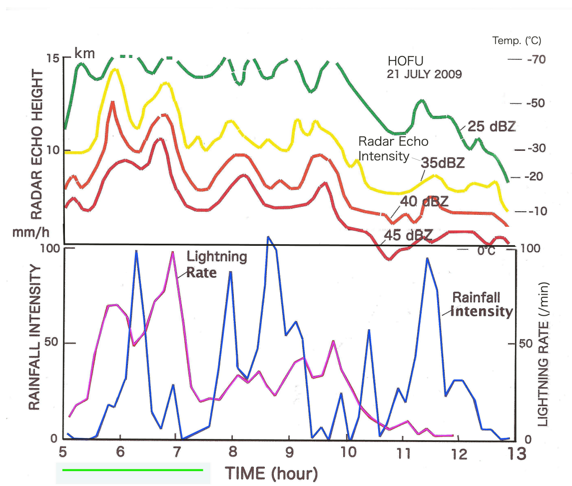

Fig. 2b. Hofu heavy rain event. Bottom: Rainfall intensity and lightning rate includes all CC and CG discharge. Top: Radar echo intensity.

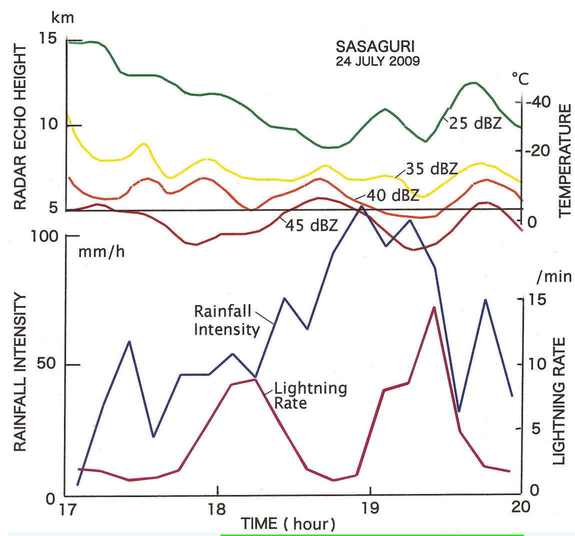

Fig. 3b. Same as Fig. 2b except Sasaguri heavy rain event.

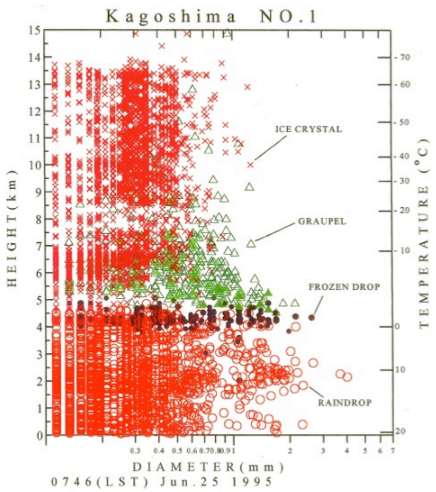

Fig.4. Kagoshima videosonde precipitation particle profile. Open red circles (raindrops), solid purple circles (frozen drops), green triangles (graupel), red xs (ice crystals).

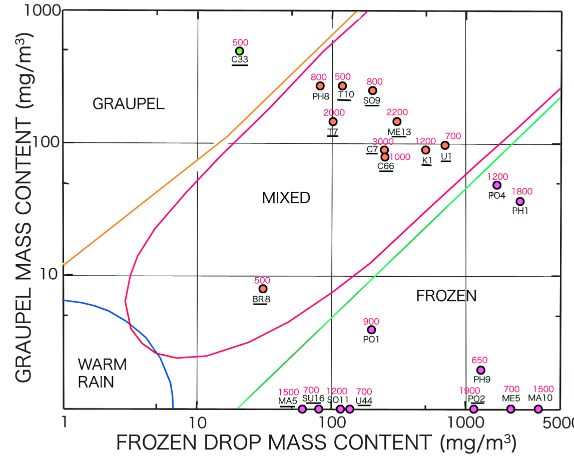

Fig. 5a. Videosonde data from East and Southeast Asian, heavy rain producing clouds. Peak raindrop mass content (>500 mg/m^3) was plotted by its peak graupel mass content vs. peak frozen-drop mass content.

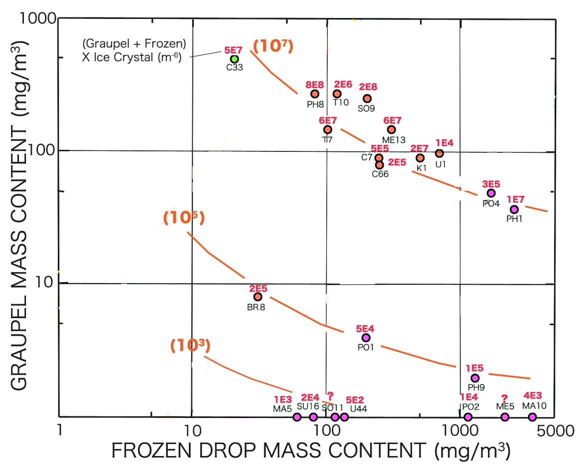

Fig. 5b. The product of peak graupel and frozen drop number densities and peak ice crystal number density.

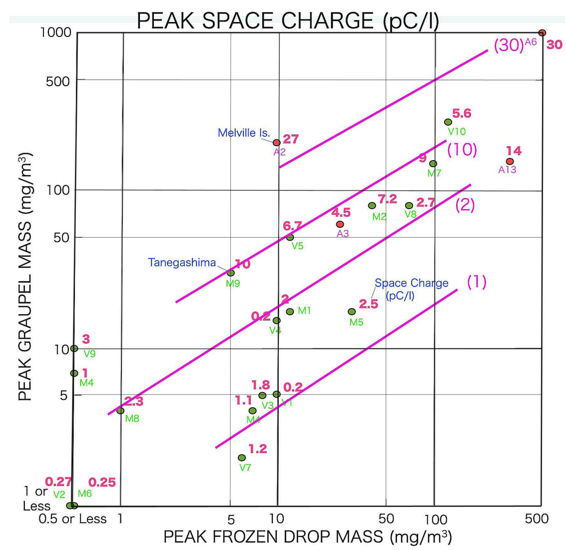

Fig. 5c. Peak particle space charge (pC/l) versus peak frozen drop and peak graupel mass contents.

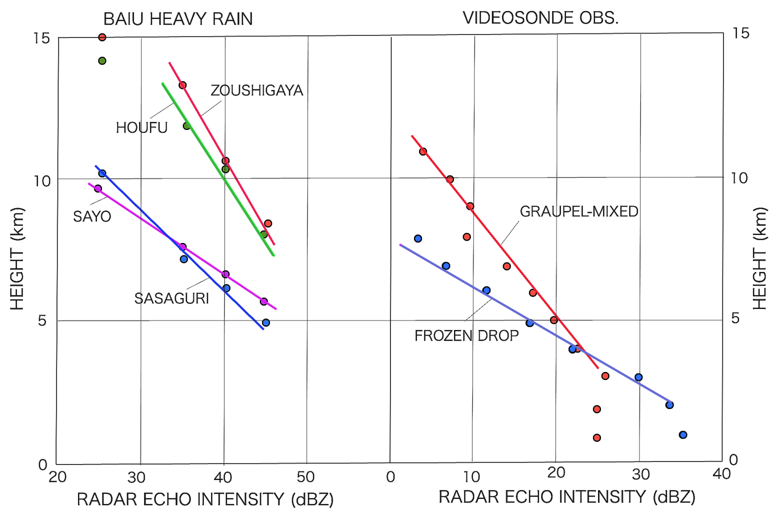

Fig. 6. Radar data. Left: For each Japanese heavy rain event, the highest altitude reached by each radar echo intensity is plotted. Right: Videosonde particle concentration data were converted to equivalent radar echo intensities, for the purpose of comparison

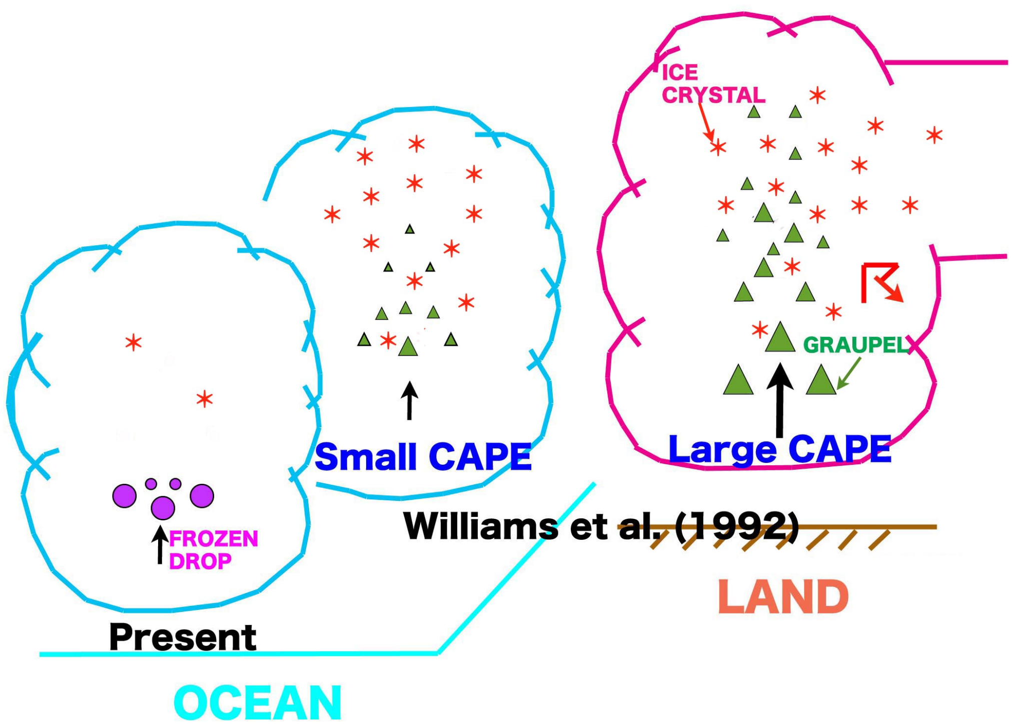

Fig. 7. Hypotheses proposed to explain the contrast between high cloud electrification over land and low cloud electrification over ocean: Center and Right: The earlier, differential updraft strength hypothesis. Left: The proposed, graupel- vs. frozen-drop-based precipitation mechanism hypothesis.