Different Precipitation Mechanisms Produce Heavy Rain With and Without Lightning in Japan

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Abstract

During summer, disturbed weather 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 three Baiu and two non-Baiu Japanese heavy rain events in 2008–2009 were compared with videosonde data from various cloud systems across East and Southeast Asia. This analysis suggests that 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.

Keywords correlation of precipitation mechanism and lightning activity in heavy rain; Baiu heavy rain and lightning activity; rain precipitation mechanisms; lightning activity and charge separation mechanism

1. Introduction

It is well established that there are two basic types of torrential rainfall: one with frequent lightning (Holle and Bennett 1997; Bauer-Messmer et al. 1997; Soula et al. 1998) and the other with little or no lightning (Petersen et al. 1999; Lang et al. 2004).

The Baiu frontal system is generated when the cold air of the northwest-Kamchatka high pressure zone to the north meets the warm, moist air of the tropical Pacific high pressure zone to the south along a west-to-east boundary which passes over the Japanese archipelago. In summer 2009, heavy rain associated with the Baiu frontal system struck Yamaguchi prefecture, at the southwestern end of Honshu, Japan (Fig. 1). Hofu city recorded 381 mm of rainfall in two days (July 20–21, 2009), leaving 15 people killed or missing. In a 100 × 100 km² area centered on Hofu city, 14,307 lightning flashes were recorded in 11
h (1301 h\(^{-1}\)). In contrast, a few days later (July 24, 2009), another torrential rainstorm struck Fukuoka prefecture, west of Yamaguchi prefecture, where Sasaguri city recorded 251 mm of rainfall in one day. However, lightning activity was relatively low, with 1015 lightning flashes recorded in 8.5 h (119 h\(^{-1}\)).

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 (Orville and Hendersen 1986; Zipser 1994; Christian et al. 2003). In addition, between the 0°C and −20°C levels, radar echo intensity decreases steeply with height (6 dBZ km\(^{-1}\)) in tropical thunderclouds but decreases slowly with height (1.5 dBZ km\(^{-1}\)) in continental thunderclouds (Szoke and Zipser 1986; Zipser and Lutz 1994; Gremillion and Orville 1999). 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.

Recently, both types of cloud, with their widely differing lightning activities and radar echo intensity lapse rates, have been observed in the same locations, including in the western North Pacific (Kodama et al. 2007), in the Texas gulf coastal region (Torancinta et al. 1996), and as noted above, in the heavy rain storms of Japan. In analyzing the two former cases, it was hypothesized that the large difference in lightning activity between storms in the same location resulted from differences in updraft strength, similar to the way in which differential updraft strength had been hypothesized earlier to account for the difference in lightning activity between land and ocean. 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.

Heavy rain without lightning was reported on the Big Island of Hawaii (Cram and Tatum 1979). Electrical activity is extremely low in warm clouds (Takahashi 1975). Polarization radar (Carey and Rutledge 2000; and others), aircraft (Dye et al. 1986; French et al. 1996; and others), and videosonde (Takahashi et al. 1999) observations all showed that cloud electrification intensifies with the appearance of graupel. And as the number concentration of graupel and ice crystals increases, lightning activity also increases (Takahashi 2012). The riming electrification mechanism is most probably the main charge separation process in thunderstorm (Reynolds et al. 1957; Takahashi 1978; Saunders et al. 1991).

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. Observations of heavy-rain-producing, Baiu and non-Baiu, Japanese clouds are compared to previous videosonde observations of heavy-rain-producing clouds conducted across East and Southeast Asia. This analysis suggests that two different precipitation mechanisms generate heavy rain, only one of which
 leads to high cloud electrification, which it generates by riming electrification. Our observations suggest that these different precipitation mechanisms may lead to different raindrop size distributions and rain cell life spans.

2. 2008–2009 heavy rain events in Japan

In 2008 and 2009, many heavy rain events occurred in Japan. From them, five major heavy rain events were selected for analysis based on the availability of constant altitude plan position indicator (CAPPI) radar data (Fig. 1, Table 1). These were centered on (1) Hofu City, Yamaguchi Prefecture; (2) Sasaguri Town, Fukuoka Prefecture; (3) Dazaifu City, Fukuoka Prefecture; (4) Sayo Town, Hyōgo Prefecture; and (5) the Zōshigaya neighborhood of Toshima City, Tokyo Metropolis. The first three were Baiu rainstorms and last two were non-Baiu rainstorms. Three Baiu heavy rain events, Hofu rain with high lightning activity and Sasaguri (Dazaifu) rain with low lightning, were investigated first. The study was then expanded to the Sayo and Zōshigaya heavy rain events, which occurred at around the same time of the year and for which CAPPI radar data were available.

Neither convective available potential energy nor cloud top height correlated well with lightning activity in the Japanese heavy rain cases analyzed in this paper (Table 1). In the lightning-inactive Sayo heavy rain event, cloud tops were relatively low (−50°C), but in the other heavy rain events, both lightning-active and lightning-inactive cloud tops reached the −70°C level. Rainfall information was derived from high-intensity rain reports issued by local weather stations (Shionomisaki Observatory 2009; Fukuoka District Meteorological Agency 2009; Tokyo District Meteorological Agency 2008; Ushiyama 2010). Radar and lightning data were supplied mainly by the Japan Meteorological Agency (JMA) which collects data across Japan. Three-dimensional radar reflectivity data were available at 10 min intervals with a 1 km vertical resolution. Radar settings were: wavelength, 5.59–5.71 cm; peak power, 250 kW; 3-dB beam width, ~1°. The lightning detection equipment used 30–300 MHz wavelength for intra-cloud (IC) discharge (interferometer method) and 30–300 kHz wavelength for cloud-ground (CG) discharge (arrival time difference method). Hofu CG data were from the Chugoku Electric Power Co., Inc. while Sasaguri and Dazaifu CG data were from Kyushu Electric Company. Kyushu Electric Company employed LPATS (Lightning Positioning and Tracking System), while Chugoku Electric Company employed the IMPACT (Improved Accuracy from Combined Technology) system, which uses both arrival time and direction finding to track lightning (Takahashi 2009). All other lightning data, including IC and CG, were from JMA. JMA estimated their CG detection rate to be 70 %, compared to visual observations of lightning (Liden Data Usage Manual, 2003, JMA). Though JMA has not reported their IC detection rate, a similar measuring system was found to have similar CG and IC detection rates when compared to lightning imaging sensor data (Boccippio et al. 2002, Christian

| City          | Observation Date (Radar Analysis Period) | Daily Rainfall (CAPE) | Lightning Count, Time (Flash Freq.) | Ratio of Intra-Cloud Discharge |
|---------------|----------------------------------------|-----------------------|-------------------------------------|-------------------------------|
| HOFU          | 21 JULY 2009 (5:00–7:30)               | 275 mm (986 J kg⁻¹)  | 14,307 flashes, 03:00–14:00 (1301 flashes h⁻¹) | 6 %                           |
| (34.0°N, 131.5°E) |                                        | Fukuoka, 00Z         |                                     |                               |
| SASAGURI      | 24 JULY 2009 (18:00–20:00)             | 251 mm (119 J kg⁻¹)  | 1015 flashes, 15:30–24:00 (119 flashes h⁻¹) | 19 %                          |
| (33.6°N, 130.5°E) |                                        | Fukuoka 12Z          |                                     |                               |
| SAYO          | 9 AUG 2009 (19:00–22:00)               | 326 mm (2388 J kg⁻¹) | 121 flashes, 00:00–24:00 (5 flashes h⁻¹) | 95 %                          |
| (35.0°N, 134.3°E) |                                        | Shionomisaki, 12Z   |                                     |                               |
| ZŌSHIGAYA     | 5 AUG 2008 (10:30–13:30)               | 134 mm (807 J kg⁻¹)  | 6212 flashes, 09:00–18:00 (690 flashes h⁻¹) | 81 %                          |
| (35.7°N, 139.7°E) |                                        | Shionomisaki, 00Z   |                                     |                               |
et al. 2003). In the present work, within the high-electrical-activity group and within the low-electrical-activity group, IC lightning frequencies were roughly comparable whether the storm was a Baiu or non-Baiu storm. This suggested that the Baiu and non-Baiu heavy rain events might be productively compared and that such a comparison might reveal a common mechanistic difference responsible for the dichotomy in electrical activity in both groups.

Wind profiles were taken from JMA mesoscale analysis data (Saito et al. 2006). All lightning counts and radar echo data are for the 100 × 100 km² area centered on the target location. “Daily rainfall” is the total rainfall for each calendar day. “Peak hourly rainfall” is the highest rainfall accumulation to occur within any 60 min period. “Transient hourly rainfall” is estimated from 10 min rain accumulation intervals and reported in hourly units to facilitate comparison.

Local time, Japan Standard Time (JST) is used in this paper unless otherwise stated.

2.1 Hofu Heavy Rain Event

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 hPa 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); the transient rainfall intensity peak reached during each event was \( \sim 99 \text{ mm h}^{-1} \) (\( \sim 6.17 \text{ a.m.}, \text{ Stage 1} \)), \( \sim 107 \text{ mm h}^{-1} \) (\( \sim 8:37 \text{ a.m. Stage 2} \)), and \( \sim 96 \text{ mm h}^{-1} \) (\( \sim 11:28 \text{ a.m. Stage 3} \)). Total lightning activity within the 100 × 100 km² area centered on Hofu from 03:00 to 14:00 on July 21 was 14,307 flashes (1301 flashes h⁻¹). 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 100 × 100 km² area, peak 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. The occurrence of both high- and low-lightning-frequency heavy rain events at different stages of the same heavy rain period might be due to the difference in the size of the space charge cell at each stage, or it might indicate that full charge separation in cloud cells does not occur during a transient stage.

2.2 Sasaguri and Dazaifu heavy rain events

On July 24, 2009, the Baiu front held stationary, centered over Tsushima Island (Fig. 3a). In Fukuoka Prefecture, Kyushu, winds at 700 hPa were from the southwest, and heavy rain struck when rain cells from the southwest merged with the main cloud cluster. At Sasaguri, a town to the northeast of Fukuoka City, daily rainfall was 251 mm and peak hourly rainfall was 100 mm. The transient rainfall intensity peak was \( \sim 111 \text{ mm h}^{-1} \) at \( \sim 18:57 \) (Fig. 3b). Lightning activity; however, was relatively low, with only 1015 flashes from 15:30 to 24:00 (119 flashes h⁻¹) within the 100 × 100 km² area centered on Sasaguri. 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.

Two days later, on July 26, 2009, low pressure developed within the stationary Baiu front over the northern part of Kyushu. This time, rainfall was heaviest in Dazaifu, about 10 km south of Sasaguri. Dazaifu daily rainfall was 277 mm, and peak hourly rainfall was 84 mm. Lightning activity was low, with only 54 flashes from 0600 to 1300 (8 flashes h⁻¹) within the 100 × 100 km² area centered on Dazaifu. Because cloud pattern, daily rainfall, peak hourly rainfall, and lightning activity were all similar to the July 24 Sasaguri heavy rain event, the Sasaguri event was taken to be representative of both, and the Dazaifu case is not further analyzed, below.

2.3 Sayo heavy rain event

On August 9, 2009, the flow of moist air from the ocean was accelerated by Typhoon Etau which was over the ocean ~ 500 km due South of Sayo (Fig. 4a). Winds at 700 hPa were from the Southeast, and rain cells from the ocean to the Southeast merged into the main rain cells at the front. Heavy rain was recorded in Hyōgo Prefecture and was heaviest in Sayo. In Sayo, daily rainfall was 326 mm and peak hourly rainfall was 89 mm. The transient rainfall intensity peak was \( \sim 96 \text{ mm h}^{-1} \) at \( \sim 20:55 \) (Fig. 4b). Lightning activity; however, was extremely low, with only 121 flashes from 00:00 to 24:00 (5 flashes h⁻¹) within the 100 × 100 km² area centered on Sayo. Here, the most lightning was IC. During the period of heaviest rain (~ 18:45–21:30), the 45 dBZ radar echo altitude...
Fig. 2a. Hofu heavy rain event. Upper: Surface weather map. Middle: Infrared Satellite image. Lower: Surface radar echo intensity profile with Hofu City marked by a circle. The area shown corresponds to the box in the Satellite image.
stayed near the melting level, and radar echo intensity decreased steeply with height (Fig. 4b).

2.4 Zōshigaya heavy rain event

On August 5, 2008, a relatively short but very intense rain event (non-Baiu) inundated a very small area centered on the Zōshigaya, neighborhood of Tokyo (Fig. 5a). A flash flood drowned five workers repairing a drainage pipe. From the Kanto area, a frontal line (non-Baiu) stretched far to the northeast over the ocean. Winds at 700 hPa were weak westerlies. The rain pattern here differed from the Baiu rain pattern. Rain cells were small (about 20 km diameter) and isolated. The rain system will be thermal thunderstorm. At Zōshigaya, peak hourly rainfall intensity was 66 mm h⁻¹, total rainfall during this event was 134 mm, and the transient rainfall intensity peak was 123 mm h⁻¹ at 12:05 (Fig. 5b). All of this rain fell in less than two hours (~11:47–13:34). Lightning activity was relatively high, with 6212 flashes from 09:00 to 18:00 (690 flashes h⁻¹) within the 100 × 100 km² area centered on Zōshigaya. IC lightning dominated. Considering that the thunderstorm cells here were rather small and sporadic compared to the broader cloud clusters of the Baiu front, the lightning activity of these Zōshigaya cells was quite high. The 45 dBZ radar echo altitude oscillated greatly, and radar echo intensity decreased slowly with increasing height.

3. Other east asian rain systems

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).
Fig. 3a. Sasaguri heavy rain event. Other than the location, see Fig. 2a for description.
The videosonde is an in-cloud, precipitation particle observation platform. While ascending through clouds tethered to a balloon, the videosonde continuously acquires video images and charge measurements of precipitation particles and transmits these data to a receiving station on the ground (Takahashi 1990). Precipitation particle mass and charge were summed in bins of altitude 500 m; peak water content and peak space charge refer to the highest of these binned measurements. Videosonde (K1) was launched into moderate rain during the Baiu season at Kagoshima (Fig. 2 of Takahashi 2006) 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 peak rain mass content was ≥ 500 mg m\(^{-3}\). This yielded 22 videosonde flights into different cloud systems at 11 locations, including three flights into Japanese Baiu clouds (T7, T10, and K1, see Figs. 6a, b), and these could be divided into three separate regimes based on their relative abundance of graupel vs. frozen drops (Takahashi 2006; Fig. 6a): (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). Earlier, we reported that lightning activity was strongly dependent upon the number concentrations of graupel, and ice crystals (Takahashi 2012). To extend this analysis, we examined ice crystal...
Fig. 4a. Sayo heavy rain event. Other than the location, see Fig. 2a for description.
concentration with respect to graupel and frozen drop contents. The sum of peak graupel and frozen-drop concentration multiplied by peak ice crystal concentration, i.e. \([\text{(peak graupel concentration)} + \text{(peak frozen drop concentration)}] \times \text{peak ice crystal concentration}\), was plotted against peak graupel mass content and against peak frozen drop mass content. The product correlated strongly with graupel mass content but did not correlate with frozen-drop content (Fig. 6b), suggesting that ice crystal production is associated with graupel production but not with frozen-drop production.

Graupel and ice crystals are both critical for riming electrification, and higher concentrations are associated with higher cloud electrification (Takahashi 2012). In contrast, increasing frozen drop concentration is not associated with higher cloud electrification, probably because ice crystal concentration in frozen-drop dominated clouds is usually low. To show this, peak space charge was compared with peak graupel mass content and peak frozen drop mass content. For example, in comparing data from the videosonde flights launched at Tanegashima and Melville Island (22 videosonde flights into different cloud systems, including clouds that did not produce rain \(\geq 500\, \text{mg m}^{-3}\)), particle space charge increased with increasing graupel content but not with frozen drop content (Fig. 6c).

We next sought to compare the heavy-rain-producing, East and Southeast Asian clouds (videosonde Fig. 4b. Sayo heavy rain event. Other than the location, see Fig. 2b for description.
Fig. 5a. Zōshigaya heavy rain event. Other than the location, see Fig. 2a for description.
data) with the clouds of the four Japanese heavy rain events (radar data) (Fig. 7). To do this, the videosonde-acquired precipitation-particle measurements were converted to radar echo intensity units by assuming that the particles follow the Marshall-Palmer size distribution.

The empirical $Z$–$R$ relation is derived as (Mizuno 2000),

$$Z_0 = 300 R^{1.47}.$$ 

Here, $R$ is rainfall intensity in mm h$^{-1}$ and $Z_0$ is in mm$^6$ m$^{-3}$. The radar reflectivity factor $Z$ is related as

$$Z = 10 \log Z_0.$$

This assumption should be valid because graupel and frozen drops are the major precipitation particles contributing to water content above the melting level. Videosonde data were converted to radar echo intensities for 14 videosonde flights into 14 cloud systems at 11 locations across East and Southeast Asia (Fig. 7-right panel). These were selected from among the flights of Fig. 6a on the basis of three criteria: (1) the major particles were not snowflakes, (2) the cloud was not in the dissipating stage, and (3) the videosonde never dropped in height during its flight.

To study the relationship between graupel and electrification, because the Graupel Regime sample size was so small, it was combined with the Mixed Regime data. Both Graupel Regime and Mixed Regime clouds had similar radar echo profiles above the melting level, suggesting that this grouping is justified. The combined group will hereafter be called, “Graupel-Mixed.”

Frozen drops were dominant in four flights (Ma5, Su16, U44, Po2), and graupel or a graupel-and-frozen drop mixture were dominant in 10 flights (C33, T10, So9, T7, ME13, U1, C7, K1, C66, BR8). PH8 was excluded from Mixed group, because the precipitation particle distribution separated into two layers. For each flight, the height and density of the particle column were described by plotting the mean altitude reached by each radar echo intensity. On
average, in the Graupel-Mixed group, compared to the Frozen Drop group, radar echo intensity decreased with height less steeply and radar echo extended to substantially higher altitudes (Fig. 7-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. 7-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), high radar echo extended to substantially higher altitudes and decreased with height somewhat less steeply. This tendency is similar to that reported in previous work on lapse rates and lightning activity (Szoke and Zipser 1986; and others). In the Sasaguri case, of the four data points, the three for the lowest altitudes fall along a straight line that when extrapolated, substantially underestimates the observed value for echo intensity at the highest-altitude data point. While the three lower-altitude data points were each derived from many cloud cells, the highest-altitude data point was derived from only a few cloud cells (as few cloud cells of this echo intensity reached that altitude) and so we are not confident that it accurately represents the general trend in the system. Because we are comparing the general, altitude-versus-echo-intensity trend of each cloud system, for the Sasaguri system, we drew a trend line using only the three lower-altitude points, excluding the potentially anomalous outlier.

The radar echo intensity lapse rate of Graupel-Mixed Regime clouds (2.7 dBZ km\(^{-1}\)) is similar to the lapse rates of the Hofu (2.1 dBZ km\(^{-1}\)) and...
Zōshigaya (2.0 dBZ km$^{-1}$) clouds. As the average lapse rate of Frozen-Drop Regime clouds (5.9 dBZ km$^{-1}$) is almost double the average lapse rate of Graupel-Mixed Regime clouds, so also the lapse rates of the Sayo (5.1 dBZ km$^{-1}$) and Sasaguri (4.6 dBZ km$^{-1}$) clouds are about double the lapse rates of the Hofu and Zōshigaya clouds. This suggests that the Graupel-Mixed precipitation mechanism was dominant in generating the heavy rain (and high lightning activity) of the Hofu and Zōshigaya events while the frozen drop precipitation mechanism was dominant in generating the heavy rain of the Sayo and Sasaguri events. The relatively small lapse rates in the Sayo and Sasaguri heavy rain events compared to the larger lapse rates of pure Frozen-Drop Regime clouds might represent the mixing of graupel into them.

The difference in lapse rates suggests a difference in precipitation particle distributions; that is, in weak lapse rate clouds, graupel dominate; while in steep lapse rate clouds, frozen drops dominate. Because graupel has a relatively low mass density, they are readily lifted up to higher levels. Conversely, frozen drops near the melting level have a relatively high mass density, and their mass will increase as they grow large by collecting the large supercooled drops that surround them, and so they tend not to be lifted higher. A large difference, therefore, is expected to be observed not only for lapse rate but also for radar echo height between graupel-dominated and frozen-drop-dominated clouds. Indeed, intense radar echo extended to higher levels in the Hofu and Zōshigaya cases than in the Sasaguri and Sayo cases, consistent with these groups having different precipitation particle distributions.

Rainfall intensity and radar echo intensity were much higher in the four Japanese heavy rain events than in the videosonde-observed clouds. Given their weaker rainfall, the videosonde-observed clouds, would also be expected to have weaker updrafts, and this might explain why their Frozen-Drop Regime and Graupel-Mixed Regime clouds display less separation in their radar-echo-intensity-versus-height curves.

Fig. 6b. Videosonde data from East and Southeast Asian, heavy-rain producing clouds. Same as Fig. 6a except that each videosonde flight is labeled with the product of its peak graupel and frozen drop number densities and its peak ice crystal number densities.
In both groups (videosonde-observed and Japanese heavy rain events), 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-lighting-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 frozen drops. 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.

4. Discussion

As reviewed in the introduction, it has been proposed that a major cause of lightning frequency variation between different clouds is updraft strength. According to this hypothesis, higher updraft strength produces larger graupel, leading to higher electrification, while weaker updraft strength produces smaller graupel, leading to lower electrification. This was first
proposed to explain the disparity between the high lightning frequency over land vs. the low lightning frequency over ocean (Fig. 8) (Williams et al. 1992; Rutledge et al. 1992), and it has since been used to explain the wide variation in lightning activity often observed in different clouds even when in close proximity geographically and in time. 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 often observed from these clouds.

Here, we propose that the critical difference that causes this divergence in electrical activity is 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. 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).

Whether graupel or frozen drops will dominate in a cloud is primarily determined by cloud nucleus concentration, which is low over oceans and high over continents. Over the ocean, low cloud nucleus concentration favors the warm rain process (Squires 1958; Twomey and Squires 1959; Twomey and Wojciechowski 1969; Albrecht 1989; Hudson 1993), leading to tall, convective clouds in which the frozen-drop precipitation mechanism generates rain. Using a cloud model, Takahashi and Lee (1978) demonstrated that when cloud nucleus concentration is low, drops grow faster due to decreased competition for the water vapor available in the cloud cell. Large drizzle drops and raindrops are formed by the time when air parcel at the cloud base reaches the melting levels. Some of

Fig. 7. Radar data from Japanese heavy rain events is compared to videosonde data from East and Southeast Asian, heavy-rain producing clouds. Left: For each Japanese heavy rain event, the highest altitude reached by each radar echo intensity (within the indicated time range) is plotted. The plotted events are Hofu (0500–0730), Sasaguri (1800–2000), Sayo (1830–2200), and Zōshigaya (1030–1330). Right: Videosonde particle concentration data were converted to equivalent radar echo intensities, for the purpose of comparison. Mean heights are presented for Graupel/Mixed Regime videosonde flights (C33, T10, SO9, T7, ME13, U1, C7, K1, C66, BR8) and Frozen-Drop Regime flights (Ma5, Su16, U44, PO2).
them freeze near the melting level. Since they need not to break up as raindrops do, they keep growing by collecting surrounding supercooled drops. Because of their higher terminal velocity, they resist updraft. Large water content is thus accumulated as frozen drops near the melting level.

Where frozen drops are dominant, the air mass is probably of oceanic origin. In the two Japanese heavy rain events with weak lightning activity, at Sasaguri and Sayo, low-altitude (700 hPa) winds were from the southwest and southeast, respectively, also suggesting that they both developed in air of oceanic origin.

The different precipitation mechanisms are expected to lead to different raindrop size distributions and rain cell life spans. Graupel Regime clouds will have a relatively steep raindrop size distribution. Graupel grows by collecting small cloud-drops, and because this is a growth mechanism available to graupel throughout the cloud, a sharp decrease in frequency with size is expected in Graupel Regime storm clouds. However, we predict a broader raindrop size distribution for clouds of the Frozen-Drop Regime. Like graupel, frozen drops can grow by collecting cloud droplets. However, frozen drops are much more numerous than graupel near the melting level (Takahashi 2006), and the frozen drops there may be able to grow by a second mechanism, that is, by collecting large, supercooled drops. This would be expected to increase the frequency of large-diameter raindrops in Frozen-Drop Regime storm clouds. Finally, rain cells are expected to be fewer and shorter-lived in the low lightning activity, Frozen-Drop Regime, because the accumulation of growing frozen drops near the melting level will accelerate rain cell dissipation (Takahashi and Shimura 2004).

5. Conclusion

Based on analysis of lightning activity in five, recent, Japanese, heavy rain events and comparison with previous videosonde observations of other heavy-rain-producing clouds, we hypothesize that the very wide range of lightning activity in Japanese storm clouds is due to the presence in these clouds of two different precipitation mechanisms. The Graupel Regime produces high lightning activity, but the Frozen-Drop Regime is relatively electrically inactive. We predict that heavy rain storm clouds with high or low electrical activity will be found to be dominated
by the Graupel or Frozen-Drop Regime, respectively. We also predict that low-lightning Baiu storm clouds will display raindrop size distributions that are broader, and rain cells that are fewer and shorter-lived, than their high-lightning counterparts.

In improving our understanding of storm systems, these results may contribute to flight safety.

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